BULLETIN

OF THE

GEOLOGICAL SOCIETY

OF

AMERICA

VOL. 19

JOSEPH STANLEY-BROWN, *Editor*

NEW YORK
PUBLISHED BY THE SOCIETY
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The Society issues a single serial octavo publication entitled Bulletin of the Geological Society of America. This serial is made up of *proceedings* and *memoirs*, the former embracing the records of meetings, with abstracts and short papers, list of Fellows, etcetera, and the latter embracing larger papers accepted for publication. The matter is issued as rapidly as practicable, in covered brochures, which are at once distributed to Fellows and to such exchanges and subscribers as desire the brochure form of distribution. The brochures are arranged for binding in annual volumes, which are elaborately indexed. To this date nineteen volumes have been published and an index to the first ten volumes.

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Irregular Publications

In the interest of exact bibliography, the Society takes cognizance of all publications issued wholly or in part under its auspices. Each author if a memoir receives 30 copies without cost, and is permitted to order any additional num-

ber at a slight advance on cost of paper and presswork; and these separate brochures are identical with those of the editions issued and distributed by the Society. Contributors to the proceedings are also authorized to order any number of separate copies of their papers at a slight advance on cost of paper and presswork; but such separates are bibliographically distinct from the brochures issued by the Society.

The following separates of parts of volume 19 have been issued:

Editions uniform with the Brochures of the Society

Pages	1– 28,	330 copies.	March	30, 1908.
"	29– 52, plates 1– 2;	130 "	"	30, 1908.
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* Bearing the imprint [From Bull. Geol. Soc. Am., Vol. 18, 1906].
† Fractional pages are sometimes included.

CORRECTIONS AND INSERTIONS

All contributors to volume 19 have been invited to send corrections and insertions to be made in their papers, and the volume has been scanned with some care by the Editor. The following are such corrections and insertions as are deemed worthy of attention:

Page 53, line 5 from top; *for* "1908" *read* 1907
" 99, " 2 from top; *for* "July 10" *read* June 10
" 122, " 4 from bottom; *for* "nebula" *read* nebulæ
" 125, " 13 from top; *for* "those" *read* that
" 126, " 19 from top; *for* "dynamic" *read* thermodynamic
" 128, " 6–7 from top; *for* "is found" *read* inferred
" 131, " 18 from top; *for* "conjealed" *read* congealed
" 136, " 9 from bottom; *for* "1893" *read* 1903
" 137, foot-note, passim; *for* "l" *read* 1
" 145, line 9 from bottom; delete how
" 403, " 5 from top; *for* "December 29" *read* December 30
" 501, " 2 from top; *for* "January 6, 1908," *read* January 6, 1909

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 19, PP. 1-28 MARCH 30, 1908

THE PROBLEM OF THE PRE-CAMBRIAN[1]

PRESIDENTIAL ADDRESS BY CHARLES RICHARD VAN HISE

(Read before the Society December 17, 1907)

CONTENTS

INTRODUCTION

Following the precedent of many scientific presidential addresses, I shall give a general review of one of the subjects which has occupied much of my time—the problem of the pre-Cambrian. Within an hour I can not consider the merits of the questions still in controversy, nor broadly cover the field mentioned; therefore I shall confine my review to the stratigraphy and nomenclature of the pre-Cambrian rocks.

The Cambrian is defined as terminating below at the base of the well recognized Olenellus fauna. In general between the Cambrian and pre-

[1] Manuscript received by Secretary of the Society February 5, 1908.

Cambrian there is an unconformity. This unconformity for a large part of the United States is profound, being the break at the base of the great Cambrian transgression.

In the early days of geology in America the name "primary" or "primitive" was given to the group of rocks under consideration. By the men who used these terms there was scarcely any attempt to apply stratigraphic methods to them. They were content with general lithological descriptions of the rocks observed.

The original Laurentian District

The working out of the stratigraphy of the pre-Cambrian of America began when Sir William Logan came to this country, in 1842. Before he took charge of the Canadian Geological Survey, Logan had had long practice in working out the difficult stratigraphy of the coal fields of Wales. He was above all else a stratigraphical geologist.

Logan had not been long in Canada before he saw that antedating the fossiliferous rocks are other sedimentary rocks, to which he applied the methods he had so successfully used in Wales. The first region in which this attempt was made was the Laurentian mountains of Canada. As a result of Logan's studies, extending through a number of years, he finally proposed in 1854 to designate the rocks of these mountains by the name "Laurentian." Later Logan appreciated that this Laurentian consisted of two parts—an upper, subordinate portion, containing limestone and gneissic rocks, presumably of sedimentary origin, and a lower, dominant mass, consisting mainly of various gneisses and granites. Still later an anorthosite formation was recognized which was regarded as newer than the formations mentioned, so it was called Upper Laurentian. The term Grenville was introduced by Logan in 1863 to designate the upper sedimentary limestone series, although he still used the term Laurentian system to cover all of the formations of the district.

Later work by Adams has shown the anorthosite series to be intrusive in the older rocks. He has also shown that some of the gneisses associated with the limestone of the Grenville series have the composition of sediments, and that some of the Lower Laurentian gneisses and granites have the composition of igneous rocks; and, further, that many of the Lower Laurentian gneisses and granites intrude the Grenville sediments.

The Hastings District

Southwest of the original Laurentian area and north of the east end of lake Ontario is the so-called Hastings series, in which work was first done

by Vennor. Here the sedimentary rocks are in vastly greater volume and the metamorphism of large areas is much less advanced than in the original Laurentian district. The later studies of Adams led him to the conclusion that there are gradations between the moderately metamorphosed sedimentary rocks, in which limestone is the greatest formation, to the intensely metamorphosed varieties, which are like those of the original Laurentian area, and he concluded that the Grenville and Hastings series are one.

A committee representing the United States and Canadian geological surveys, consisting of Messrs Adams, Barlow, Coleman, Cushing, Kemp, and Van Hise, accepted Adams' conclusions and agreed to extend the term Grenville, previously applied in the Laurentian district only, to the similar formations in the Hastings and Adirondack districts. In the report of this committee the term Laurentian was restricted to the acid gneissic and granitic rocks, many of which are intrusive into the sedimentary series, in accordance with the usage recognized in the report of the committee upon the Lake Superior region, to be mentioned later[2] (see page 12).

The report of the committee showed that there is in the Madoc area of the Hastings district a series of rocks, consisting largely of conglomerates, felsites, slates, and schists, which rest unconformably upon a limestone-bearing series. The existence of a physical break in the sedimentary series was thus recognized, but its importance and the position of the upper series were left undetermined. The last word upon this district is by Miller and Knight,[3] who hold that they have proved that—

"much, at least, of what has been called the Hastings series, consisting of limestones, conglomerate, and other fragmental rocks, is much younger than, and forms a well defined unconformable series with, the typical crystalline limestones and associated fragmental rocks of what has been called the Grenville series proper. The view that the Grenville and Hastings constitute one series, the former being a more highly altered phase of the latter, is no longer tenable."

Miller and Knight also think that in places they have found the Keewatin lava floor on which the Grenville series has been deposited. According to them,

[2] Report of a special committee on the correlation of the pre-Cambrian rocks of the Adirondack mountains, the "Original Laurentian area" of Canada and eastern Ontario, by Messrs F. D. Adams, A. E. Barlow, A. P. Coleman, H. P. Cushing, J. F. Kemp, and C. R. Van Hise. Journal of Geology, vol. 15, 1907, pp. 191-217.

[3] Grenville-Hastings unconformity and the probable identity in age of the Grenville limestone with the Keewatin iron formation of the Lake Superior region, by Willet G. Miller and Cyril W. Knight. Sixteenth Report, Bureau of Mines, Ontario, 1907, pp. 221-223.

"an ancient Keewatin lava has, in places, been subjected to a little denudation before the deposition of the Grenville limestone, which fills the cracks and openings in the ropy surface of the lava. Unconformably above the Grenville limestones and Keewatin lavas or greenstones rest the conglomerates and other sedimentary rocks, including limestones, which the present writers class as Huronian."

Thus, according to Miller and Knight, there is in the Hastings area a series of rocks bearing limestone which is the equivalent of the Grenville; but to the upper series of rocks, which were not given a definite place by the International Committee, they would apply the term Hastings and place this series in the Huronian.

Miller and Knight do not expressly indicate whether the unconformity which they recognize is at the same horizon as that discovered by the International Committee, but presumably this is the fact. If this be so, their work determines the point left unsettled by that committee as to the importance of this unconformity and shows that it has great structural significance. The discovery that the upper series contains a limestone formation as well as the Grenville series is of great importance, for it means that it yet remains to discriminate separately upon the geological map the areal extent of the two series containing the different limestone formations of the Hastings district.

Until these two series are separately mapped and the limestone is distributed between them, I am unwilling to commit myself as to the probable position of the Grenville series. If, as Miller's work intimates, the Grenville has been laid down upon an ancient eroded Keewatin floor, it may be equivalent to the lowest of the Huronian series, to be later discussed. Whatever the position of the Grenville proper, the upper series of the Hastings district, which may be called the Hastings series, in all probability is of Huronian age, probably Middle Huronian or Lower Huronian.

The original Huronian District

After having been several years in Canada, Sir William Logan began systematic work upon the north shore of lake Huron, with Alexander Murray as his assistant. In this Lake Huron work the name of Murray should always be associated with that of Logan. The former furnished the broad ideas; the latter carried them out with great patience in an extremely rough country, covered with a dense forest, of which there was no map other than the land surveys. No one who has not attempted to work out intricate geology in the tangled forest of an unbroken wilderness without adequate maps, and been tortured by the innumerable insects

of the northern woods, can appreciate the physical and mental stamina required for successful geological work under such circumstances.

On the north shore of lake Huron, Logan and Murray found rocks which antedate the Cambrian, or, as the lowest formations of the fossiliferous rocks were called in those days, the Silurian. While these rocks were considerably altered, they were not changed from their original condition so much that they could not be readily recognized in the field as quartzites, graywackes, slates, conglomerates, limestone, etcetera, and therefore the series was regarded by Logan as non-metamorphic. The sedimentary formations on the north shore of lake Huron were found to be arranged in a definite order, allowing as precise mapping as the sedimentary rocks of Wales. Below this sedimentary series Logan and Murray found another system, composed mainly of granites and gneisses, which is similar to the rocks comprising the larger masses of the Laurentian mountains. Logan supposed this lower series to be of the same age as the rocks of those mountains, and he therefore carried the name Laurentian to the north shore of lake Huron, and there applied the term to the lowest series, although the Laurentian of this area contains no sedimentary rocks like the so-called Upper Laurentian, or Grenville, in the original district. But the newer set of rocks, resting on the older series, he recognized to be different in lithological character from any of the rocks of the Laurentian area. He also saw that in the conglomerates of the upper series are very numerous pebbles and boulders identical with the rocks of the older series, and he therefore inferred that the newer series rested unconformably above the older. Because the newer series had not been greatly changed from their original condition and because of the inferred unconformity, Logan pursued the same method he had followed for the Laurentian district—that is, he applied a local term to the set of rocks which he believed to be younger than the Laurentian. Since they skirt the north shore of lake Huron, he naturally called them Huronian. This was in 1858.

In 1883 Irving visited the original Huronian area, and found a contact between the lowest Huronian sediments and the Laurentian granites which showed a great unconformity to exist between the two; also he recognized that the chloritic schists of Logan, which he supposed to be metamorphosed sediments, are basic igneous rocks, largely volcanic.

Later, Pumpelly and I, studying the Huronian series somewhat closely, found an unconformity within the Huronian sedimentary series between Logan's limestone formation and the upper slate conglomerate. In 1902 further close studies by Leith and myself showed this unconformity to be important; also we found the chloritic schists which Logan placed with

the Huronian to be unconformably below the Huronian, and to be intruded by the granite, and therefore in age more nearly related to the Laurentian than to the Huronian.

Finally, north of Sudbury, some distance north of lake Huron, is another series, which Bell placed as Cambrian on the Canadian maps, but which is now agreed to be pre-Cambrian and which our studies show probably to be unconformably above the Huronian immediately north of lake Huron, mapped in detail by Logan, but in Logan's general map included in the Huronian.

Thus, in the region north of lake Huron are two groups of rocks separated by unconformities. The lower consists subordinately of basic volcanic and dominantly of granitic and granitoid gneisses, the acid rocks being intrusive in the basic. According to the usage advocated by the International Committee, on the Lake Superior region below mentioned the volcanics are Keewatin and the granites and gneisses Laurentian. The upper group comprises three unconformably sedimentary series, which may be called Lower, Middle, and Upper Huronian.

Later Work of Logan and Others

The work of Logan in the Laurentian mountains and of Logan and Murray on the north shore of lake Huron occupied many years, yet the areas of the districts mapped were almost infinitesimal as compared with the vast expanses of pre-Cambrian rocks of Canada. In this early careful detailed work the rocks which had been called Laurentian were mainly light colored, pink or gray with intermediate shades, of the granitic order, or, as we would perhaps say at present, gneissoid granites and granitic gneisses. The Huronian series of rocks were largely composed of green and dark gray sediments with intermediate shades and subordinate masses of light colored quartzites and limestones, but gray and green were the prevailing tones; also it is to be remembered that Logan placed with these series green chloritic volcanic rocks, which later work has shown to be unconformably below them.

A period of rapid reconnaissance mapping in Canada now followed the early epoch of close systematic work upon confined areas. The colors gave the clew to the geologist. Here was an easier method than digging out the stratigraphy from the forests, which method required years of laborious work for small areas. The pink and gray rocks of granitic types were Laurentian, and the dark gray and green rocks, whether sedimentary or igneous, were Huronian. Thus was inaugurated the chromatic epoch of mapping the pre-Cambrian formations, which is at least a score times as rapid and easy as the early methods of Logan and Murray

and which, incidentally it may be remarked, is about a twentieth part as accurate.

We have here an illustration of an error which has crept into geology again and again, not only with reference to the pre-Cambrian, but with reference to other formations. As a result of patient, careful work, taking into account all the facts, a stratigraphic problem is worked out. Not one criterion, but many are used. But perhaps one is conspicuous. This is selected and applied broadly in other regions, ignoring all others. As a result, the rocks grouped under the method are classified upon a certain basis, but this is no longer the original basis. If the geological maps which have been produced by the color method of mapping had been so called, so that it was understood that the term Laurentian meant acid granitic and gneissic rocks, and that Huronian meant quartzites, graywackes, conglomerates, and basic igneous rocks, without reference to relations, no harm would have been done. The defect consisted in regarding this work as structural.

The Lake Superior Region

REVIEW OF THE INVESTIGATIONS IN THIS FIELD

After having worked out the stratigraphy of the north shore of lake Huron, Logan visited lake Superior, and there recognized a group of rocks in which the copper deposits occur, which he regarded as different from and at a higher horizon than the Huronian. He called these rocks the upper copper-bearing series in contrast to the Huronian of the north shore of lake Huron containing the copper deposits of Bruce mines. This upper series is the one which was later known as the Keweenawan.

We must now pass from Canada to the United States to find the continuation of the early methods of work of Logan and Murray. In Michigan and Wisconsin, state geological surveys were organized. In Michigan the work on the copper-bearing rocks was handled by Pumpelly and Marvine, and that upon the iron-bearing rocks by Brooks. Brooks, Irving, and Wright were all engaged in studying on the iron-bearing rocks of Wisconsin. In these districts there were great economic deposits of iron and copper which justified the most careful mapping.

Prior to the investigations by the state surveys in this region, a large amount of good preliminary work had been done by Foster and Whitney and others, but this work was of the same general type as that of other American geologists antecedent to the days of Logan and Murray. These geologists and their defender, Wadsworth, insisted that the pre-Cambrian rocks were indivisible on a structural basis and to all of them the term

Azoic was applied. But Pumpelly, Marvine, Brooks, Irving, and Wright, with unflagging energy and infinite patience, resumed on the south shore of lake Superior the true stratigraphic methods of the great Canadian geologists. The names of Pumpelly and Marvine must be connected ever with the stratigraphy of the Keweenawan rocks. Their papers on this series are classic today. Similarly the names of Brooks and Irving must be associated always with the stratigraphy of the iron-bearing or Huronian rocks. In this pioneer work Brooks wore himself out in ten years, so that he never was able to resume active geological work.

If one who was familiar with the Lake Superior region in these early days, and therefore knows the conditions under which Brooks' and Irving's work was done in an unbroken forest, will examine their geological maps of the Marquette, Menominee, and Penokee districts, he can not but be filled with admiration at the amazing insight of these men, who were able to put into a consistent story the scraps of geological history which they were able to gather from the occasional outcrops in the wilderness.

Brooks, Pumpelly, and Irving recognized the same major divisions on the south shore of lake Superior which Logan and Murray had recognized on the north shore of lake Huron. That is to say, there was a great complex of basement rocks and above them essentially sedimentary series which contain the iron and copper deposits.

THE BASEMENT COMPLEX

The lower or basement group was found to consist dominantly of granites and gneisses which were believed to be in the same stratigraphic position as the similar rocks of the Laurentian of the north shore of lake Huron. Irving also found on the south shore a series of dark gray and green schistose rocks, proved by George H. Williams to be largely of volcanic origin, which he recognized were structurally more closely associated with the granite and gneiss called Laurentian than with the sedimentary iron-bearing series. In this respect Irving made an advance upon the work of Logan, who on the north shore of lake Huron placed the equivalent rocks with the Huronian.

Williams proved that the granites and gneisses of the basement series intrude the schistose volcanic series, the relations being the same as those which were later found to obtain on the north shore of lake Huron. Our further studies show that this volcanic series is an extensive one. When this fact was realized and it was appreciated that it was the oldest series in the Lake Superior region, the term "Mareniscan" was proposed in 1892 to designate it.[4]

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[4] Bulletin no. 86, U. S. Geological Survey, p. 191.

Prior to the introduction of this term, in 1886, Lawson had proposed the name "Keewatin" for a great series of rocks, largely volcanic, which occurs in the Lake of the Woods region. His reason for proposing the name was that the series was different from any Huronian or Laurentian series which had been described, and he was uncertain as to its stratigraphical position. When the work of the United States Geological Survey was extended to the international boundary, the detailed work being done by Leith, Clements, and Bayley, it was found that Lawson's Keewatin series is in the same position—indeed, is a continuation of the Mareniscan of the United States. Since the term Keewatin was proposed prior to that of Mareniscan, although the latter was first defined in the broad sense, the International Committee, with my concurrence, accepted the former term to designate the ancient volcanic series of the basement complex.

Of the different geologists, Clements has made the most careful petrographic study of the Keewatin, and his map of the Vermilion district shows the formation to consist of a great variety of basic and intermediate rocks, the major portion of which are volcanic rather than plutonic. A peculiar ellipsoidal greenstone is especially characteristic and has a widespread occurrence. My own general studies of the Keewatin, where best exposed over broad areas in a number of districts, have led to the conclusion that it is essentially a submarine volcanic group, although of course including many intrusive rocks.

When the United States geologists (Clements, Leith, Bayley, and Merriam) mapped the Vermilion district of northeastern Minnesota they found that associated with the Keewatin is an iron-bearing formation which is productive. The more closely the district was studied, the plainer it appeared that the thick productive formation is in all probability upon the top of the igneous rocks in some places between the two, there being a slight erosion interval marking unconformity. Smaller beds of iron formation material seem clearly to be within the Keewatin greenstones.

Later studies in Canada have shown that an iron-bearing formation similar to that of the Vermilion district is widely associated with the Keewatin, for example, in the Hunters Island, Atikokan, Matawin, Michipicoten, and other districts.

THE HURONIAN SERIES

Irving and Brooks found the series of the south shore above the basement complex to consist dominantly of sedimentary formations such as limestones, quartzites, slates, etcetera, which may be mapped stratigraph-

ically as are any other sedimentary formations. Thus in all essential respects they found this series to be like the original Huronian of the north shore of lake Huron, and they therefore gave the group this name. Later the work of Irving and myself showed that there was an unconformity between the basement complex and the Huronian. My later work led me to the division of the Huronian into two unconformable series, which were called Lower Huronian and Upper Huronian. Still later work by Seaman showed that my Lower Huronian is divisible into two unconformable series, and thus it follows that on the south shore of lake Superior, as on the north shore of lake Huron, there are three unconformable series to which the term Huronian have been applied, and which may be called Lower, Middle, and Upper.

The upper of these series is the so-called Animikie. If it were practicable to generally separate this series from the two lower, this would be most advantageous; for in that case the upper Huronian would have a distinctive name, and the term Huronian could be restricted to the latter two. This would be a great gain in the matter of clearness of nomenclature, and also this usage would give the term Huronian a scope almost exactly equivalent to its usage as first applied on the detailed maps of Logan and Murray in the area immediately adjacent to lake Huron. But as yet it has not been practicable to separate the Animikie from the other divisions of the Huronian over broad areas, and therefore apparently for the present the latter term must be continued to cover all three series, allowing the term Animike to be used for the upper series where it can be discriminated.

In this connection it may be mentioned in passing that the break between the Animikie and the Keewatin, which has been recognized from the first, Lawson emphasizes as the greatest which obtains in the Lake Superior region. In various localities the Animikie rests directly on the Lower Huronian or the Keewatin, and the Middle or both the Middle and Lower Huronian are therefore absent. In the former case the unconformity at the base of the Animikie represents two unconformities and the intervening series. In the latter case the unconformity at the base of the Animikie represents three unconformities and the two intervening series. In this case the unconformity corresponds to a greater interval of time than can possibly be represented by the unconformity between the Lower Huronian and the Keewatin, because such unconformity includes this unconformity and also two others with their intervening series.

However, a geological classification must be made on the basis of a full succession rather than on the basis of a succession in which a part of the

column is absent. Where the Animikie occurs in districts which show the next underlying series, the Middle Huronian, there is no evidence that the unconformity at the base of the Animikie is any greater than that between the Middle and Lower Huronian or between the Animikie and the Keweenawan. Doubtless the different inter-Huronian unconformities do represent variable lapses of time, but we have no data from which we can determine which unconformity is greater than the others. So far as the evidence goes, the unconformity between the Animikie and the Middle Huronian is certainly not nearly so important as that between the Lower Huronian and the Keewatin.

In the Marquette and Penokee districts the contrasts, from every point of view, between the Keewatin and Lower Huronian are amazing. The schistosity of the Keewatin existed before the Lower Huronian and abuts at right angles against the sedimentary beds of the latter series. In contrast with this, the unconformities within the Huronian series, including that at the base of the Animikie, are like other moderate unconformities in sedimentary series. I think no one who has studied the facts in the field where the full succession from the Animikie downward occurs can arrive at any other conclusion than that the unconformity between the lower Huronian and the Keewatin is the greatest of the Lake Superior region (see pages 12-13).

On one point in reference to the Lake Superior structure there has been no controversy. This is the relation of the Keweenawan and Huronian. As already seen, Logan recognized that this series is at a higher horizon than the Huronian. Brooks' studies of the relations of the Huronian and the Keweenawan on the south shore of lake Superior led him to the belief that there is an unconformity between the two. Irving found evidence of this unconformity upon the north shore of lake Superior. My own later studies in the Penokee district show that this unconformity, which there is between the Keweenawan and Upper Huronian (Animikie), is one of very considerable magnitude, the differential erosion represented by it amounting to thousands of feet. Studies by W. N. Smith, Clements, and myself in northeastern Minnesota and Canada have still further emphasized the importance of the unconformity between the Keweenawan and Animikie, although here the amount of erosion is not so great as in the Penokee district.

All who have made extensive studies in the Lake Superior region, with the exception of the later Michigan geologists, have agreed that all the series yet considered, from the Keewatin to the Keweenawan, inclusive, are unconformably below the Upper Cambrian sandstone. Moreover, they hold that the nature of this unconformity is such as to make it

highly probable that the Keweenawan is pre-Cambrian; but from this view Lane dissents.

REPORT OF THE INTERNATIONAL COMMITTEE

The results of the above studies in the Lake Superior region, largely by the United States geologists, were accepted in 1904 by the Joint Committee of Canadian and United States Geological Surveys, consisting of Messrs Adams, Bell, Lane, Leith, Miller, and Van Hise. After visiting the Lake Superior and Lake Huron regions, they recommended the recognition of the succession, structure, and nomenclature given below:

CAMBRIAN—Upper sandstones, etcetera, of lake Superior.
    Unconformity.
PRE-CAMBRIAN.
    Keweenawan (Nipigon).
        Unconformity.
    Huronian.... { Upper (Animikie).
            Unconformity.
        Middle.
            Unconformity.
        Lower. }
        Unconformity.
    Keewatin.
        Eruptive contact.
    Laurentian.

The report of the International Committee gave no major grouping of the above series. In this paper the Keweenawan and the Huronian are together included in the Algonkian, and the Keewatin and Laurentian in the Archean. This grouping will not be discussed at this point, except in relation to the magnitude of the unconformity between Huronian and the Keewatin. Already it has been indicated that the field studies of the United States geologists show this unconformity to be more conspicuous and widespread than any of the others. This conclusion, largely based upon studies in the Lake Superior and Lake Huron regions, upon both sides of the boundary, has been confirmed by studies over extensive areas by W. G. Miller, provincial geologist of Ontario, and R. W. Brock, the recently appointed director of the Canadian Geological Survey. Miller has recognized this break at many localities and has emphasized it in his various papers. Brock in a recent report upon the Larder Lake district recognized a great break at this horizon. He says in reference to rock systems on opposite sides of the break:[5]

"It is interesting to find at such widely separated points as lake Superior, lake Huron, Cobalt, and the Height of Land, the same rocks, showing the same

[5] Sixteenth Report of the Bureau of Mines, part 1, 1907, p. 206.

relationships, falling into the same scheme of classification; thus confirming the idea that the rocks as grouped represent great and widespread systems, separated by profound alterations of geological conditions during great time intervals."

THE MAJOR DIVISIONS OF THE PRE-CAMBRIAN

In regions of America other than those already mentioned there was little attempt in early years to apply stratigraphic methods to the pre-Cambrian rocks. They were regarded as an indivisible group. As already noted, the men who thus treated the pre-Cambrian rocks as a unit first used the term primary and primitive. Later the term Azoic gained favor, on the ground that in these rocks no fossil evidence of distinct life had been found, and it was believed that they were formed before life existed upon the globe. This term contrasted the ancient rocks with the fossiliferous, and therefore zoic, formations.

As knowledge of the pre-Cambrian grew, the protest against the assumption that life did not exist during this time became more and more vigorous. To avoid the difficulty and to meet the needs of those who wished to view the pre-Cambrian rocks as a unit, the name Archean, or ancient, was suggested by Dana in 1872. This term very happily met the needs of the general geologist, who did not wish to undertake detailed work in the pre-Cambrian, and thus it rapidly found favor. For many years this term was widely used to include all the pre-Cambrian formations, and to the present time it is thus used by certain geologists.

After the work of the Wisconsin and Michigan surveys was well advanced and after studies had been made in other parts of the world, proving that there are series of sedimentary rocks antedating the Cambrian, which are radically different from a basement set on which they rest, and when it was, moreover, shown that this set of sedimentary rocks was one of large magnitude, Irving held that the great period of time represented by the upper pre-Cambrian group was long enough, so that it should be recognized as of the first order—that is, it was worthy of a place of the order of Paleozoic and Mesozoic. He further pointed out that the rocks of this time, while furnishing no definitely recognizable fossils, contained life. This was conclusively shown by the large amount of carbonaceous material and graphite in the slates, and it was believed that the limestones and iron ores pointed in the same direction. Since the nature of the life of this time was unknown, the name "Agnotozoic," first suggested by Chamberlin, was brought forward by Irving, as was the term "Eparchean." "Proterozoic" was also considered by Irving for the place, but was rejected by him. Agnotozoic gained a small place in literature, but Eparchean was never much used. However, to Agnotozoic it

was objected that while the nature of the life is now unknown, in the future it is likely to become known.

In my correlation bulletin upon the Archean and Algonkian,[6] while I did not exclude Agnotozoic from the classification of the pre-Cambrian, I inserted Proterozoic opposite to Agnotozoic as the name of the era and expressed my preference for the former. In a later paper I dropped the latter term altogether.[7] Of the two terms, Proterozoic has increased in favor and Eparchean has disappeared from current usage.

It is my own belief that Irving did not care particularly what term was used for the pre-Cambrian sedimentary series. That was a matter of small consequence. The idea was the thing for which he strove.

Shortly after Irving had shown to most of the thinking geologists that the pre-Cambrian group of sedimentary rocks must be recognized and discriminated from the basement group, his unfortunate death occurred, and I was asked to continue the direction of the work of which he had had charge in the Lake Superior region. In 1889 a conference was called at Washington to consider the nomenclature to be placed on the proposed geologic atlas of the United States. It was decided at this conference that zoic terms should not appear on the maps, although they might be used in the text. The largest divisions on the map were to be systemic. Thus the terms Silurian, Cretaceous, etcetera, but not Paleozoic and Mesozoic, were to be placed on the maps. This decision raised the question what should be done in reference to the Agnotozoic or Proterozoic.

The fossiliferous groups of rocks are divided into periods and correlated on the basis of fossil evidence. In the Lake Superior region is a fauna called Silurian, similar to faunæ in the Silurian rocks of New York and of Wales, but no way has been found to tell whether a pre-Cambrian sedimentary series of the Lake Superior region is equivalent to one which occurs in the Grand Canyon district, in Scotland, or in China. What, then, should be done? In the Lake Superior region we have not one, but four series of sedimentary rocks separated by unconformities, all separated by another unconformity from the basement group below, and by still another unconformity from the Cambrian above. Which of these series should be correlated with the Grand Canyon series of the Colorado? And may not the Grand Canyon series be equivalent to one of the unconformities in the Lake Superior region? To these questions there were no answers. The science of geology had not sufficiently advanced to correlate on a physical basis from province to province, nor has it to the present time. When the physical history of the conti-

[6] Bulletin no. 86 of the U. S. Geological Survey, p. 493.

[7] Principles of North American pre-Cambrian Geology. Sixteenth Annual Report of the U. S. Geological Survey, p. 762.

nents is worked out, when we know more about paleogeography, when we learn how extensive are the great unconformities, we may be able to correlate pre-Cambrian rock series from province to province and even from continent to continent, but as yet this can not be safely done. Because of this fact, it was decided that only a single period should be recognized as equivalent to the Proterozoic, and for this place the term Algonkian was proposed and accepted. Who proposed the term Algonkian the record does not show. It is not a competitor of Keweenawan or Huronian, for it includes them both; and it has never been proposed to define either of these terms for general use to cover the essentially sedimentary pre-Cambrian series of the entire earth. While Algonkian is given a systemic position upon the atlas of the United States, its definition entitles it to rank as a group, and this rank is recognized in this paper.

At the same conference at which the term Algonkian was adopted for the upper group of the pre-Cambrian, it was proposed to use the term Archean for the basement complex below. On the atlas sheets of the Geological Survey this term was assigned a systemic value, but like Algonkian it is here recognized as representing a group. This definition of the term Archean has been objected to by a number of geologists, because before it was made the term had been very generally used to indicate all pre-Cambrian rocks. The difficulty with this use of the term is that under it two rock groups are placed together which are fundamentally different. The Algonkian group is much more nearly allied to the Paleozoic than to the Archean, as the term is here used. Indeed, the only essential difference between the Algonkian and the Paleozoic is the almost complete absence of definite fossil forms in the Algonkian. To attempt to include both pre-Cambrian groups under one name would result in making two groups of rocks to appear to be alike when as a matter of fact they are radically different. When this point is appreciated it is clear that the term Archean is especially adapted to designate the older group of the pre-Cambrian. In confining the term to the oldest group of rocks, the essential intent of Dana in proposing the term is carried out, so far as this can be done and still make the nomenclature used represent the facts of geology.

In short, the same plan has been followed with reference to the term Archean that has been applied to the terms Keewatin and Laurentian—that is, to define them so as to make them correspond as nearly as possible to published maps on which they have been placed, and at the same time make them mean a definite thing rather than two or more different things.

Those who have commonly used the term Proterozoic rather than Algonkian have naturally substituted Archeozoic for Archean, and thus

the fundamental dual division of the pre-Cambrian with the group of geologists that prefer the zoic terms is Proterozoic and Archeozoic. This classification is adopted by Chamberlin and Salisbury in their text-book.

The question now arises as to which pair of terms is preferable for common use—the above, or Algonkian and Archean. The convenience of the terms Algonkian and Archean to represent the two divisions of the pre-Cambrian has been somewhat generally recognized, and besides appearing on the geological atlas of the United States and in the publications of American geologists, they have found favor in Europe.

Thus Algonkian and Archean are the major divisions for the pre-Cambrian found upon the official geological map of France, published in 1905 under Michel-Levy as inspector general and compiled by a committee consisting of thirty-five geologists of that country, with the assistance of a committee of fifty other geologists. These committees include practically all of the eminent geologists of France. It is therefore safe to say that the consensus of opinion of the geologists of that country, in accordance with that of the geologists of the United States Geological Survey, is in favor of the terms Algonkian and Archean for the primary divisions of the pre-Cambrian.

The wisdom of the conclusions of the geologists who selected the terms Algonkian and Archean for the two major divisions of the pre-Cambrian has since been confirmed by considerations which have developed since the adoption of the terms. As has been seen, when the terms Agnotozoic and Proterozoic were proposed by Irving in the sense now conveyed by Algonkian, it was known that the rocks there placed contained positive evidence of life, but it was supposed that the inferior group of the pre-Cambrian contained no evidence of the existence of life. It has since been ascertained that in the Archean all the evidences of life shown by the Algonkian exist, with the exception of the few imperfect fossils which are now known in the latter group. Thus there arises, if zoic terms are to be used, the necessity for the introduction of another zoic term for the Archean (and, as has been seen, Archeozoic has been suggested); or, if this be not done, it is necessary to extend one zoic term to cover all of the pre-Cambrian rocks to the base of the earth formations.

The objection to a dual zoic division for the pre-Cambrian rocks is that their life is not known to be different. When we say Paleozoic and Mesozoic, we understand the terms to indicate a great known faunal difference. We think not so much of the rocks, their lithological contrasts and the differences of the physical conditions of their formation, as of the life contrast. The rocks which contain a Paleozoic fauna are Paleozoic; those which contain a Mesozoic fauna are Mesozoic. The separa-

tion of the rocks of the pre-Cambrian into Proterozoic and Archeozoic premises a fundamental difference in the fauna of the two eras for which there is no evidence. In short, the zoic division is an unverified assumption which the future may or may not justify.

On the other hand, this objection can not be raised against the terms Algonkian and Archean. Their use is justified by the facts in the field, which inevitably lead to the dual classification of the pre-Cambrian formations on a physical basis. The above gives sufficient reason for continuing to adhere to them.

However, the great physical contrasts of the Archean and Algonkian and the profound unconformity separating the two, marking one of the greatest physical revolutions of the world, doubtless does correspond to great life changes. There has been a tendency to place more and more emphasis on the physical breaks between the Paleozoic and the Mesozoic, and the Mesozoic and the Cenozoic, and to regard the differences of life of these eras as largely due to physical revolutions; consequently we should expect the great physical revolution separating the Archean and Algonkian to have resulted in important life changes; and while I shall use the terms Algonkian and Archean because they correspond by definition to the physical facts on which the dual division of the pre-Cambrian is made, if others prefer the terms Proterozoic and Archeozoic, I shall not quarrel with them, after having pointed out that fossil evidence can not be given to justify this life classification, and that the use of these terms is based on faith in future progress rather than on achieved results.

It is evident from the above outline of the history of the pre-Cambrian stratigraphy and nomenclature that the geologists working on these formations are much nearer to agreement than they were a score of years since. The point on which there is perhaps most difference among geologists, and especially between the United States geologists and some Canadian geologists, is the emphasis by the former on the distinction between the Algonkian and the Archean. Since there has been some dissent as to the fundamental importance of this discrimination, it may be well to mention briefly the principles on which it is based.

In the first place, as already indicated, between the two groups an unconformity is general. Moreover, this unconformity is believed to be the most distinctive and widespread exhibited by the pre-Cambrian formations. However, to justify fully the emphasis placed on the dual division of the pre-Cambrian, the separating unconformity needs support by other contrasts. Some of the more important of these are as follows:

1. The Archean is a series dominantly composed of igneous rocks, largely volcanic and for extensive areas probably submarine. Sediments

are subordinate. The Algonkian is a series of rocks which is mainly sedimentary. Volcanic rocks are subordinate. Of course, by the latter statement it is not meant to imply that vast masses of volcanic rocks were not extruded in Algonkian time. In this respect this group is precisely the same as any of the fossiliferous groups of rocks. Thus there was a great outburst of vulcanism in Tertiary times and volcanic rocks covering areas of hundreds of thousands of square miles and thousands of feet in thickness were poured out. Yet we characterize the Tertiary era by the sediments and their fauna rather than by the igneous rocks. Similarly, in stating that the Algonkian is a series of rocks which is mainly sedimentary, it is meant to say that these are the rocks which give the keys for their discrimination, and this is so notwithstanding the fact that, for instance, in the Keweenawan and the Grand Canyon groups volcanic rocks are very abundant.

2. The Algonkian sediments, where not too greatly metamorphosed, are similar in all essential respects to those which occur in the Paleozoic and later periods. When the Algonkian rocks were laid down essentially the present conditions prevailed on the earth. The Archean rocks, on the other hand, indicate that during this era the physical conditions had not yet become such as to widely lead to the orderly succession of sedimentary rocks like those being formed today. To this practical distinction, which I have repeatedly emphasized, Chamberlin and Salisbury in their recent textbook on geology give a theoretical interpretation. According to their views, the Archean complex was formed before the weathering processes and hydro-atmospheric work became prominent, whereas the fact that the rocks of the Algonkian are in every essential respect like those which are being now formed they regard as evidence that the conditions had become favorable for mature weathering. The atmosphere and hydrosphere were the dominant dynamic agents, and they worked on land areas covered by vegetation.[8] The Archean group, on the other hand, appears to antedate the time in which the sedimentary agencies were dominant.

3. The folding and metamorphism of the Archean are on the whole very much further advanced than the Algonkian. The Archean complex has an intricacy of structure which is approached only locally by the Algonkian. Schistosity, gneissosity, and other secondary structures are very widespread. While often the foldings and faultings of the Algonkian rocks are complex and the secondary structures widespread, in these respects the group does not approach the intricacy of the Archean.

For the Keewatin division of the Archean where katamorphic changes

[8] Textbook of Geology, by T. C. Chamberlin and R. D. Salisbury, vol. 2, 1906, p. 139.

have prevailed, the secondary minerals—epidote, chlorite, and calcite—are very conspicuous and characteristic. Where anamorphic changes have taken place, often due to abundant intrusives or powerful dynamic action, or both, these minerals are likely to be less important.

4. Martin and Leith have noted that the Archean and Algonkian contrast in their surface expression, often making it possible to separate areas of the two groups on a physiographic basis. Thus, in the Lake Superior region the Archean is characterized by a peneplain with small elevations, for the most part without regular outlines, sometimes controlled by the prevailing northeast-southwest structures of the Lake Superior region. The Algonkian, as a rule, has bolder relief and its elevations are strongly linear, in general parallel to the structure of the Lake Superior basin. The distinction in the physiography of the Archean and the Algonkian is of course dependent on the features mentioned above, and especially on the fact that the former is essentially igneous and the latter essentially sedimentary. Erosion working upon diverse materials gave different expressions.

In consequence of all of the above differences it follows that ordinary stratigraphic methods may be applied to the Algonkian, while such methods are not applicable at all, or only with extreme difficulty, to the Archean. The discriminations for the few areas of Archean mapped in detail are mainly lithological. This fundamental distinction has been recognized in practice from the days of Logan and Murray. Every stratigraphical geologist who has been willing to do detailed work has had little difficulty in mapping the Algonkian, unless subsequent intrusions have been vast in amount and the metamorphism profound, whereas in only a few areas has it been practicable to map the Archean rocks on a structural basis, except as to the divisions Keewatin and Laurentian and the occasional subordinate masses of sediments.

To the dual division of the pre-Cambrian emphasized it has been objected that it can not everywhere be applied. To this objection instant agreement is made. It may be equally well said that the Paleozoic can not everywhere be separated from the pre-Paleozoic. In the Sierra Nevada these groups are not yet satisfactorily discriminated. For the coast ranges the same point might be made as to the difficulty of separating the Mesozoic from the pre-Mesozoic. The fact is, the classification of rocks must be made from areas where the physical conditions are favorable for making discriminations and where the succession is full—not in areas where the conditions are unfavorable and the succession imperfect. Wherever it is not practicable to separate the Algonkian and the Archean precisely, the same plan may be followed as that used where

it is impossible to separate the Paleozoic and pre-Paleozoic or the Mesozoic and pre-Mesozoic. In such cases the rocks may be called pre-Mesozoic, pre-Paleozoic, or pre-Cambrian, as the case may be.

It has been further objected that the classification of the pre-Cambrian is largely based on studies in the Lake Superior and Lake Huron regions; this is true, but these regions are a part of the greatest pre-Cambrian region of the world, and studies have gone sufficiently far in other parts of the great Canadian pre-Cambrian area to show that it is applicable for a large portion of the region, and, as will be seen later, to the other great regions of the world in which the most extensive studies of the pre-Cambrian have been made (see pages 21-27).

Specifically it has been objected to the classification that it could not be applied in eastern Canada, where the metamorphism is most extreme—that is, that it has not been determined to which group the Grenville belongs. However, if Miller and Knight are correct in their recent conclusions, it appears that as far east as the Hastings district the dual division of the pre-Cambrian is applicable. In this district the Archean group comprises the Laurentian and Keewatin. The upper series of sediments, to which Miller restricts the term Hastings, belongs to the Algonkian. The position of the Grenville series of the district below the Hastings yet remains to be certainly determined, and this leaves open the position of the Grenville, of the original Laurentian, and the Adirondack districts. But, considering the rapidity of the progress of the last few years, it is not too much to expect that we shall soon know where to place the Grenville series, and thus be able to distribute all the rocks of these districts between the Archean or Algonkian.

A final point which may be raised against the dual division of the pre-Cambrian is that we can not know that the plane between the Archean and Algonkian is at the same horizon in geological provinces far removed from each other. This is undoubtedly true within somewhat narrow limits, but so characteristic are the features of the two groups that I have come to believe that in almost any of the regions which have been closely studied the rocks may be divided between the more ancient group, during which the peculiar conditions resulted in the formation of Archean rocks, and a later group, formed under ordinary circumstances.

By the above it is not meant to imply that the Archean era ended in all parts of the world at the same time, for this is extremely improbable. But unquestionably the Archean as a whole represents a time the major portion of which antedates the major portion of the Algonkian. We have precisely the same difficulty as to exact correlation in reference to the Paleozoic and Mesozoic, the separation of which is made upon the

basis of fauna, that we have in reference to the Archean and Algonkian. It is not to be supposed that the characteristic Mesozoic fauna appeared in all parts of the world at the same time. Indeed, it is probable that after this first appeared in some favored portion of the globe a long time was required before the fauna had opportunity to migrate to distant parts of the world. In consequence the rocks of the remote district deposited during the time of migration would be called Paleozoic, although of the same actual age as the lower part of the Mesozoic, in the region where the fauna of this era originated. Indeed, Huxley many years ago recognized this principle to be of such importance that in 1862 he suggested a modification of the word homologous (homotaxis) to represent the rocks that have the same fauna, and thus escape the implication given by the word contemporaneous.[9]

Applications of the Proposed Classification to Regions other than the Great Northern Area

REFERENCE TO STUDIES IN OTHER AREAS

Aside from the great Canadian area, the largest areas of pre-Cambrian rocks which have been closely studied are those of western America and the northern part of the eastern continent, especially Scotland, Finland, and China. In each of the areas the dual divisions here advocated obtain.

THE CORDILLERAN REGION

In most of the early work in the western part of the United States the term Archean was applied to the pre-Cambrian rocks, no attempt being made to divide them on any other basis than lithology. The more careful work of recent years shows that there are in numerous regions, illustrated by the Uncompahgre mountains, the Grand Canyon district, Utah, and Montana, very extensive and thick series of rocks which belong in the Algonkian; also in this region there are extensive areas of Archean rocks. Indeed, it is certain that in the Cordilleran region is a vast geological province in which the Algonkian rocks have a great development, and that these rocks rest unconformably upon a basement complex having all the characteristics of the Archean.

SCOTLAND

For Scotland, it is fortunate for this discussion that the final results of the many years' work of Peach, Horne, and others on the Highlands are at last available. The splendid memoir of the Geological Survey of

[9] Discourses, biological and geological essays, by Thomas Huxley, vol. 8, p. 276.

Great Britain on that region has just appeared. The succession given for the old rocks of the western Highlands is as follows:[10]

III. Cambrian....	3. Dolomites and limestones with certain fossiliferous zones. 2. Serpulite grit and fucoid beds yielding the Olenellus fauna. 1. Quartzites with worm-casts in the upper portions and false-bedded grits below.
	(Unconformability—Plane of marine denudation.)
II. Torridonian..	3. Sandstones and dark micaceous shales. 2. Thick series of coarse sandstones and grits with conglomerate bands. 1. Dark and gray shales with calcareous bands, fine-grained sandstones and grits with epidotic grits at the base.
	(Strong unconformability, highly eroded land surface.)
I. Lewisian.....	2. A great series of igneous rocks intrusive in that complex in the form of dikes and sills. 1. A fundamental complex, composed— (*a*) mainly of gneisses that have affinities, both chemically and mineralogically, with plutonic igneous products; and (*b*) partly of crystalline schists, which may be regarded as probably of sedimentary origin.

As to the importance of the unconformity between the Torridonian and the Lewisian, Horne says:[11]

"One of the most impressive features in the history of the Lewisian gneiss is the abundant evidence of prolonged denudation between the cessation of the terrestrial movements just described and the deposition of the Torridon sandstone. During the protracted interval represented by this denudation the gneiss plateau formed a land surface which was carved into lofty hills with craggy slopes and deep valleys. This fragment of primeval Europe has been preserved under the pile of coarse Torridonian grits and sandstones which is now undergoing slow removal by the agents of waste. The observer may climb one of these Archean hills, following the boundary line between the Lewisian rocks and the younger formation, and note, step by step, how the subangular fragments of horneblende-schist that fell from the pre-Torridonian crags are intercalated in the grits and sandstones, thus indicating the slow submergence of the old land surface beneath the waters of Torridonian time. Between lake Maree and loch Broom it is possible to determine the orientation of these buried valleys and to prove that some of the hills exceeded 2,000 feet in height."

In the memoir the Lewisian system is often referred to as the "Fundamental Complex" in exactly the same sense as we have used the term in the Lake Superior region for the pre-Algonkian group. Indeed, the Scotland Fundamental Complex has all the characteristics of that of the Lake Superior region. After years of work by several men, much the larger part of the Lewisian is mapped as "undifferentiated"—that is, it has not been possible in western Scotland, with the splendid exposures of

[10] Memoirs of the Geological Survey of Great Britain. The geological structure of the northwest Highlands of Scotland, 1907, pp. 9-10, 33.

[11] Ibid., p. 4.

the region, and with 6-inches-to-the-mile ordnance maps of the highest quality, to separate the Fundamental Complex into formations, except for small areas. Probably nowhere else in the world are the opportunities better to make such separation if this were possible, and certainly no other geological survey has spent more than a small fraction of the time given by the Scotland survey to a small area of the Fundamental Complex.

The petrographic descriptions show that the Lewisian is dominantly composed of igneous rocks, of which the granitic type is most abundant, and that the sediments are extremely subordinate. The latter rocks include "mica-schists, graphitic schists, quartz-schists, siliceous granulites, limestones, dolomites, and cipolins."[12]

The relations of the sediments of the Lewisian to the igneous series have not been entirely worked out. Horne says:[13]

"There is no clear evidence that these types are intrusive in the former, but in certain places the two are so intimately associated as to suggest that the rocks of igneous origin may have been injected into those of sedimentary origin. On the other hand, there is undoubted proof that, north of lake Maree, the altered sediments rest on a platform of gneiss and are locally overlain by gneiss with basic dikes, the superposition of the gneiss on the sediments being there due to folding and thrusting."

In the strongest possible contrast with the Lewisian is the Torridonian. Here ordinary stratigraphic methods apply and the system has been divided into three divisions or formations. It is clear that under the general classification advocated in this paper the Torridonian is Algonkian and the Lewisian Archean.

While the foldings, faultings, intrusions, and metamorphisms of the Archean have been so extreme and the relations of the different rocks so intricate that upon the general geological maps there has been no attempt to subdivide the Fundamental Complex, the descriptions show that in the central district basic rocks are developed in great force with subordinate amounts of ultra basic rocks, and that in the northern and southern districts the acid rocks are dominant. Moreover, it is stated that the basic rocks are the oldest group and are intruded by the acidic gneisses. Thus we apparently have in the Archean complex the equivalent of the Keewatin and Laurentian, as we use these terms in America, with like relations.

FINLAND

In Finland for many years Sederholm has been at work on the pre-Cambrian rocks. His studies there result in a classification which is closely analogous to that of the Lake Superior region. His succession is as follows:

[12] Memoirs of the Geological Survey of Great Britain. The geological structure of the northwest Highlands of Scotland, 1907, p. 75.
[13] Ibid., p. 4.

Classification of the pre-Cambrian Rocks of eastern Fenno-Scandia

Names of the subdivisions.		Supercrustal rocks.	Infracrustal rocks.
Jotnian		Diabases, sandstones, labradorites, conglomerates.	Rapakivi-granites.
		Unconformability.	
Jatulian	Upper Jatulian (Onegian).	Augite-porphyries and their tuffs, "metabasites," anthracite, dolomites, slates, sandstones.	
	Lower Jatulian	"Metabasites," dolomites, quartzites and quartzitic sandstones, conglomerates.	
		Unconformability.	Post-Kalevian granites, injecting the Kalevian and older rocks, thus forming "veined gneisses."
Kalevian	Upper Kalevian	"Metabasites," quartzites, conglomerates.	
		Unconformability.	
	Lower Kalevian	"Metabasites," talc- and chlrorite-schists, dolomites, phyllites, quartzites, and quartzitic schists (often glassy), conglomerates.	
		Unconformability.	Post-Bottnian granites, injecting the Bottnian and older rocks, thus forming "veined gneisses."
Bottnian		Uralite-porphyries and their tuffs, plagioclase-porphyrites, conglomerates, phyllites, leptites, etcetera.	
		Unconformability.	Post-Ladogian granites, diorites, amphibolites, etcetera, injecting the Ladogian and older rocks, thus forming "veined gneisses."
Ladogian		Phyllites and mica-schists, glassy quartzites, conglomerates (?), "metabasites," dolomitic limestones, hälleflintas, etcetera.	
Katarchæan		Granitic gneisses, "metabasites," etcetera.	

From this succession it appears that in Finland there are at least four pre-Cambrian sedimentary series. For the Jotnian, Jatulian, Kalevian, and Bottnian, Sederholm makes exactly the same point as has been made with reference to the Algonkian. He says:

"At least as far back as during Bottnian time, the climate conditions were not sensibly different from those of later geological periods, as shown by the existence of rocks, which in spite of their metamorphic character show themselves to be sediments with the same regular alteration of clayey and sandy material ('annual stratification') as the glacial clays of that same region, explainable only by assuming a regular *change of seasons*."[14]

He further says that the problem of the pre-Cambrian stratigraphy has been solved "in a decidedly actualistic direction." While Sederholm is too cautious to make any definite correlations with the Lake Superior region, he suggests that the Jotnian is similar to the Keweenawan of North America, the Jatulian equivalent to the Upper Huronian (Animikie), and that the Kalevian is perhaps similar to the Lower Huronian of North America. This suggested likeness is even greater when it is remembered that what was originally called the Lower Huronian is now divided into the Middle and Lower Huronian, and that the Kalevian is divisible into two unconformable series.

These sedimentary series together constitute the Algonkian. Unconformably below these are two series of rocks, the upper called the Ladogian, and this series is intruded by the granites and gneisses of the Katachean. Thus Finland has the two divisions of the Archean which correspond to the Keewatin and Laurentian. The only essential difference is that in the Ladogian, equivalent in position to Keewatin, the sedimentary rocks seem to be more important relatively than in America.

It is plain that the major dual classification of the rocks of Finland into Archean and Algonkian is justified.

CHINA

In China the work of Richthofen showed that the pre-Cambrian rocks have an extensive development, and some of the sediments here belonging he tentatively correlated with the Huronian. The recent work of Willis and Blackwelder has placed the pre-Cambrian stratigraphy of northern China on a systematic basis.

According to Willis,[15] "A provisional classification of the Wu-t'ai and limiting systems in the type locality is as follows:"

[14] Op. cit., p. 95.
[15] Research in China, vol. ii, Systematic Geology, by Bailey Willis, p. 4.

Hu-t'o system (Neo-Proterozoic).	Tung-yü limestone...... Tóu-ts'un slates.........	Slates, limestone, and quartzite.
	Unconformity.	
Wu-t'ai system (Eo-Proterozoic).	Si-t'ai series............	Chiefly chlorite schist; quartzite conglomerate at the base.
	Unconformity.	
	Nan-t'ai series...........	Siliceous marble, jasper quartzite, and schist.
	Unconformity.	
	Shï-tsui series...........	Mica schists, gneiss, magnetite quartzite, and basal feldspathic quartzite.
	Unconformity.	
T'ai shan complex (Archean).	....	Basal complex of varied gneisses and younger intrusives.

The descriptions of the Archean, or basement complex, show that it consists dominantly of gneisses, probably largely derived from igneous rocks. Within these gneisses are various intrusives among which granite predominates. Very subordinate masses of sedimentary materials are found. In short, the descriptions of this complex show that it has all of the characteristics of the Archean. The four sedimentary series unconformably above the Archean are composed of rocks which were originally muds, grits, conglomerates, and limestones. In other words, they have all of the characteristics of the Algonkian.

There is thus a remarkable similarity between the Archean and the Algonkian of China and similar groups in North America. Indeed, the number of certainly recognized groups of sedimentary rocks of pre-Cambrian age are precisely the same as the Lake Superior region. Willis suggests that the three lower series which he groups into the Wu-t'ai system are equivalent to the Huronian of the Lake Superior region, which also is divisible into three unconformable series. This would leave the Hu-t'o system to be correlated with the Keweenawan. However, it would not be well to too strongly emphasize the close correlation suggested; but certainly the similarity of the succession is astonishing and suggests the possibility that in the future we may yet be able to correlate the unconformable series in the Algonkian in provinces separated as far from one another as the Lake Superior region and northern China. The similarity of the succession in Finland gives additional emphasis to this suggestion.

In the classification of the Algonkian presented by Willis for China he introduces into the nomenclature of the pre-Cambrian the words "Neo-Proterozoic" and "Eo-Proterozoic." I wish to question this suggested practice, since I can see no philosophical basis on which such a division can be made; nor do the facts as described seem to me to require any such division. Indeed, no adequate reason is advanced or even suggested for

the selection of one unconformity rather than another of those in the Algonkian as the basis of the division. If the use of these terms results in the practice becoming at all general, it will be believed by the students beginning geology and soon by the geologists themselves that Eo- and Neo-Algonkian or Proterozoic in one region correspond with those of the other, and this would be certain to lead to error. I know of no region in which emphasis on one break in the Algonkian more than others is justified, and if this be not the case, the division is purely theoretical rather than factitious. In short, I foresee confusion and no advantage in the arbitrary introduction of the two proposed terms which have no philosophical basis or definite facts in the field which justify them; for their use amounts to the introduction of zoic terms for the divisions of the Proterozoic, and thus the objection made (pages 16-17) to Proterozoic and Archeozoic for the major divisions of the pre-Cambrian applies with much greater force to Eo and Neo divisions of the Proterozoic.

Concluding Statement

In view of the foregoing considerations I present the following classification of the pre-Cambrian as representative of the best current views:

Algonkian......	One or more series in various geological provinces separated by unconformities. To this series local names are applicable.
Unconformity.	
Archean........	Keewatin. Eruptive unconformity. Laurentian.

Whether the physical contrasts which separate the Archean and Algonkian are such as to justify the belief that corresponding to them are two life groups which may be called the Proterozoic and Archeozoic, I leave the future to determine, and adhere to the terms which have arisen as a result of inductive studies of pre-Cambrian geology.

Those who decline to accept a dual zoic division of the pre-Cambrian may still favor a single zoic term to comprise the two groups. Thus Emilé Haug, professor of geology in the University of Paris, in his text-book on geology, which has just appeared, so uses the term Agnotozoic. But if the consensus of opinion turns in this direction, it would be better, I think, to use Proterozoic rather than Agnotozoic as the life term. If the term Proterozoic be decided on for all pre-Cambrian rocks, for the two major divisions of the Proterozoic, the terms Algonkian and Archean clearly have precedence and right of way from every point of view, and this Haug recognized by making them the major divisions of his Agnotozoic. This clearly emphasized the standing these terms have gained and to which their clear definitions and general applicability entitle them.

It has also been suggested, but, so far as I know, never in print, that the term Proterozoic be extended to the bottom of the column, and that the two divisions of the Proterozoic thus defined be Earlier and Later. This proposal would amount to an indirect dual division of the pre-Cambrian emphasized in this paper. Such usages would simply introduce other terms for the major divisions of the pre-Cambrian having a meaning equivalent to that of Archean and Algonkian. The only result of the acceptance of the proposals, so far as I can see, would be the avoidance of these terms. The ideas of those who as a result of many years' work have formulated the fundamental principles upon which the division of the pre-Cambrian is based would be taken, but their terms rejected and other terms introduced in their stead which, as terms merely, are very objectionable.

In closing I wish to express my strong belief that the dual division of the pre-Cambrian into two great groups of rocks seems now as firmly established as the division between any other two groups; indeed, the major contrasts between the Archean and Algonkian, in the character of the rocks and the earth conditions which they represent, are probably greater than between any other two. The only other two which have anything like such contrasts are the Algonkian and the Paleozoic, and this difference is not in the nature of the materials or the physical conditions obtaining during their depositions, but in the absence of definitely recognized life forms in the older and the presence of a highly developed fauna in the newer. Also the division of the Archean into Laurentian and Keewatin is firmly established, and Archean is entitled to a group place in the geological column.

It is also clear that the Algonkian should have the place of a group in the geological column. The succession includes four unconformable series for at least two regions, and, according to Sederholm, five in Finland. If in the future it is possible to divide the Algonkian on a systemic basis, as the Paleozoic has been divided into Cambrian, Silurian, Devonian, and Carboniferous, this should be done. If this can be accomplished, the terms Huronian, Animikean, Keweenawan, etcetera, would become systemic terms.

Finally, I may say that the working out of the criteria under which the Algonkian may be divided into series which may be correlated from province to province is the great problem immediately before the pre-Cambrian stratigraphical geologist. Considering the progress which has been made in the past, this problem should by no means be regarded as hopeless. When solved the stratigraphy of the pre-Cambrian formation to Archean time will be placed on as satisfactory basis as the post-Cambrian.

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BEGINNING AND RECESSION OF SAINT ANTHONY FALLS[1]

BY FREDERICK W. SARDESON

(Presented by title before the Society December 30, 1907)

CONTENTS

INTRODUCTION

It is now 30 years since Professor N. H. Winchell first discussed the history of Saint Anthony falls and 20 years since his final description of "The Recession of the Falls of Saint Anthony" was published.[2]

The conclusions which he then reached have stood without revision or notable modification to this time. Both his description of the sharply defined gorge in which the Mississippi river runs from the falls at Minneapolis to near its junction with the Minnesota river and his interpretation of the gorge as the work of the gradually receding waterfall appear to have been generally accepted as final. The Saint Anthony gorge stands therefore today with that of Niagara falls, as one of the great geological timepieces by which the duration of time since the Glacial period may be calculated.

The gradual recession of Saint Anthony falls for the distance of about 8 miles in about 8,000 years, marking the time since the final melting of

[1] Manuscript received by the Secretary January 21, 1908.

[2] Geological Survey of Minnesota, Fifth Annual Report, 1877, p. 175. Final Report, vol. II, 1888, p. 313.

the glaciers from the north, as calculated by Winchell, seems fully evident from the phenomena and data as he represents them to us. His presentation of the subject is such that little discoverable evidence would

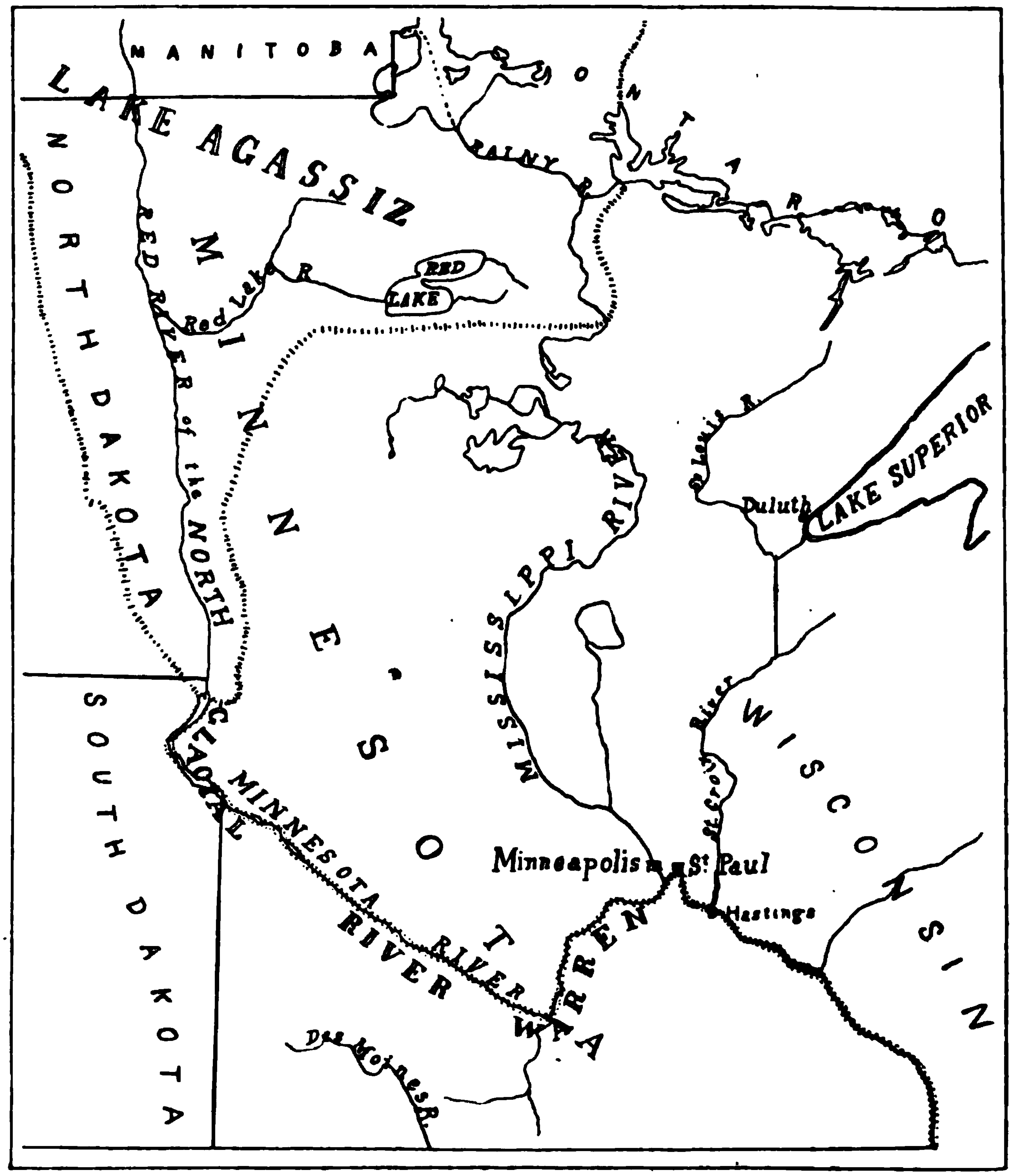


FIGURE 1.—*Map showing the general Relation of Glacial Lake Agassiz and River Warren to the Minnesota and Mississippi Rivers*

appear to have escaped his attention, and therefore no great modification or reversal of his conclusions might be expected.

More than 10 years ago I came by accident upon evidence which had been previously overlooked, and which led me to think that Winchell's interpretation might be open to important modification. This idea was

shared by my fellow-student, Arthur H. Elftman, to whom I am indebted for assistance also in some resurveying of the gorge. That the matter is here presented is due to the friendly suggestion of Frank Leverett, Dr Warren Upham, and Professor C. W. Hall.

In the following paragraphs the general method and results of Winchell's work on "The Recession of the Falls of Saint Anthony" are adopted, as are also the particulars of the same in so far as newly discovered evidence does not demand revision.

In 1890 Dr U. S. Grant announced[3] a discovery that the gorge in which Minnehaha creek flows from the falls of the same name to its confluence with the Mississippi river is in greater part the gorge of an abandoned arm of the river rather than that of the creek. His discussion of this particular feature brings out the additional detail in regard to the recession of Saint Anthony falls, namely, that the falls upon a smaller arm or stream receded proportionately less than that upon a larger arm or stream and the whole rate of recession is lessened by the dividing of the falls. Grant's conclusions are in accord with Winchell's. Evidently Doctor Grant took no note of certain terraces which stand within the abandoned gorge which he described.

I shall adopt in this paper the general results of Doctor Grant's study, with such addition as the evidence of terraces within the gorge requires. It is in fact from studying these terraces and similar ones in another abandoned gorge which I had found some 10 years ago, and later still others along the main gorge, that I have been led to revise for myself, first Grant's interpretation of Minnehaha gorge and then Winchell's account of the Saint Anthony Falls recession. It is my aim at this time to consider, in the light of new evidence, especially the beginning and early stages of Saint Anthony falls and the gorge at Fort Snelling. The entire history of the gorge and its relation to events of the Glacial period are included.

Contrasting Valleys of the Mississippi and Minnesota Rivers

At the junction of the Mississippi and Minnesota rivers the valleys present a strong contrast. The valley below the junction and that of the Minnesota above the junction are one, in that they are continuous in direction and are alike in being one-half mile or more wide, flat bottomed, and bordered by steep slopes 100 feet or more high. In contrast, the Mississippi valley above the junction runs at an angle with that below,

[3] "Account of a deserted gorge of the Mississippi near Minnehaha falls." American Geologist, vol. 5, 1890, p. 1.

and is a veritable gorge, only a fourth of a mile wide, over 100 feet deep, its steep talus-covered sides crowding the river. This relation is shown in figure 2.

For several miles in each direction from their junction these valleys are cut into the same geologic formations. The features in which the valleys are alike are therefore referable to influence of the ground rock forma-

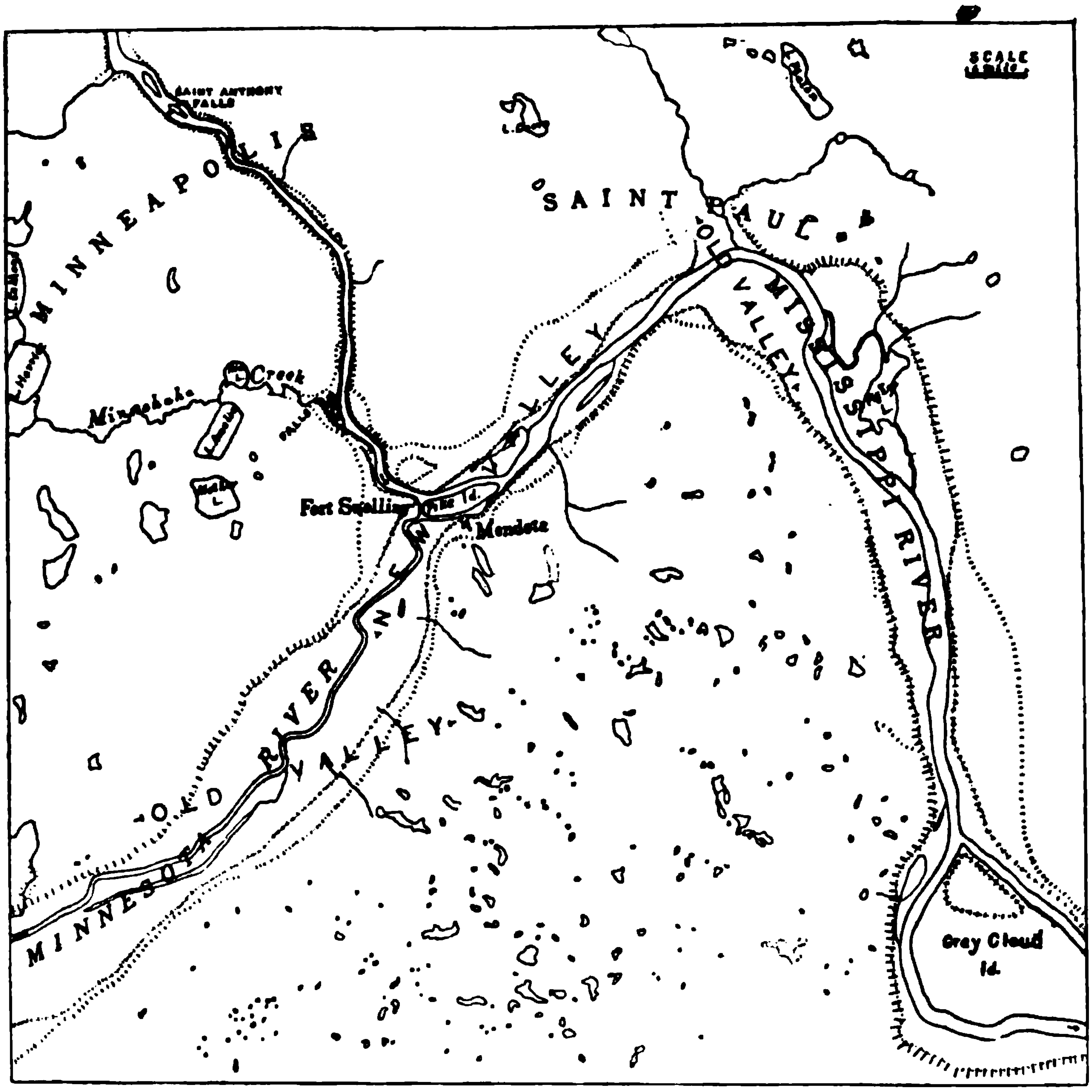


Figure 2.—*Map of the Minnesota and Mississippi Rivers near their Confluence*

Showing the relation of old and new valleys and of the upper and lower scarps bounding the terraces of the rivers

tions, while the contrasting differences are due to other causes, namely, to the different streams which made the valleys.

It has been heretofore supposed that the large, broad Minnesota-Mississippi valley is an "old" valley, in contrast to the gorge of the Mississippi, which is a "young" valley. The walls of the latter are fresh or talus-covered only, while the walls of the former have been described as

"old." In fact, the walls of the larger valley from 2 miles above the confluence of rivers to 6 miles below it are "young." That which N. H. Winchell[4] and others have written about the Minnesota and Mississippi course being "old" is true above and below the limits just mentioned. There the glacial drift lies down over the walls of the valleys.

The old valleys and new valleys referred to here are respectively pre-Glacial and post-Glacial valleys. Understanding of the distinction between them involves some general knowledge of the geologic formations of this region. Not including alluvial deposits, dune sands, talus, etcetera, the formations are the following:

(1) The glacial drift, consisting of loose boulder-clay, sand, and gravel from 0 to 100 feet or more thick, is the topmost geologic formation.

(2) Next is the base of the Galena (Trenton) series, comprising practically horizontal strata with eroded upper surface. From 0 to 80 feet of shale overlies 35 feet of limestone. For the greater part the shales are absent and the glacial drift rests on the limestone, which consists of two beds, namely, about 15 feet of massive limestone on 18 feet of laminated limestone. At the base of the latter the strata are shaly for 2 or 3 feet.

(3) The next subjacent formation is the Saint Peter sandstone, which is over 150 feet thick and passes below the rivers' levels. It is friable, easily eroded, and the removal of it by streams causes the several cascades of the region, which plunge over the persisting ledge of limestone. The top of the Saint Peter sandstone and the limestones is practically level, so that the height of any waterfall here is determined by the depth to which the sandstone is excavated by the stream. The steep sides of the valleys also are generally due to the easily eroded Saint Peter sandstone and the lateral cutting by the streams, by which the more firm limestone ledge is brought out, often as a cliff skirted by a talus slope.

The valleys in the neighboring region about the confluence of the Mississippi and Minnesota rivers may be classified into three kinds:

A. Old valleys, with cliffs or slopes covered by undisturbed boulder-clay or other glacial drift. Some of the old valleys are quite or entirely buried. Lakes Minnetonka, Calhoun, and others lie in such drift-covered valleys.

B. Reexcavated old valleys, which were partly buried by glacial drift, but later are occupied by streams again.

C. New valleys, which have been made since the glacial deposits were made and whose cliffs are not covered by glacial drift.

In short, the last, or Wisconsin, glacial drift was deposited or filled over all preexisting valleys in this vicinity, leaving it for later streams to either reexcavate the old valleys or cut new ones. The valley and gorge from Saint Anthony falls to the junction at Fort Snelling is clearly a new course made by the Glacial and Recent Mississippi. The valley of

[4] Geological Survey of Minnesota, Fifth Annual Report, 1877, p. 176.

the Minnesota, with that of the Mississippi below the confluence, as s has been heretofore considered as a pre-Glacial valley, reexcavated by Glacial river, the river Warren, and its successor, the Minnesota.

It is my view that the larger valley, the Minnesota-Mississippi cou from 2 miles above Fort Snelling to 6 miles below it (see figure 2) also not pre-Glacial, but is a new course cut by the glacial floods and river Warren. The pre-Glacial course may have run by a now bu valley south of the present course—that is, from a few miles above] Snelling, eastward, in the direction of Hastings, or Gray Cloud isl there joining the present Mississippi's valley. The pre-Glacial river responding to the Mississippi may have entered the Minnesota va above the present confluence, coming by way of the present lake Mi tonka and Purgatory creek. At Saint Paul the new course of the r joins another pre-Glacial valley, which it follows thence southeastwar

The history of the two contrasting valleys at the confluence of Minnesota and Mississippi rivers is therefore the same excepting in matter of magnitude and changes of the rivers which made them. rock formations are alike and the same lime rock ledge and fresh t slopes bound their sides. Only in size the valleys are contrasted, i cating that the Minnesota valley originally carried the main stream, now the tributary.

The glacial river which followed the present Minnesota valley thence the Mississippi was the main stream at the time of the ice-ret As shown by terraces in the Minnesota valley[5] and by the scarp above lime rock bench which lies between Fort Snelling and Saint Paul, river flowed for a time at a high level, to or above the present 820- contour line. At that stage it was one mile wide in its steep-sided cl nel at Saint Paul. It spread out over a large part of the present Snelling reservation. Its bottom was above the limestone ledge. Co spondingly the Glacial Mississippi was about one-half mile wide, as i cated by scarps and terraces.

As noted by Winchell,[6] there could have been no Saint Anthony at that high stage of the river. The flood in the Minnesota R valley must first "recede," or rather the channel from Saint Pau Fort Snelling must be cut down below the limestone ledge, before falls could have formed at Fort Snelling. In what exact manner channel was cut down is somewhat uncertain. It may be noted, how (see figure 2) that this valley is double—that there is one dist

[5] Warren Upham: Geological Survey of Minnesota, Final Report, vol. ii, 1888, p.

[6] Geological Survey of Minnesota, Final Report, vol. ii, 1888, p. 338.

channel below the other. The higher lies above the limestone ledge and is bounded by clay-shale and glacial morainic deposits, into which it has the appearance of having been cut by a large stream. The other is half as wide as the higher one and lies below the limestone ledge and in the Saint Peter sandstone, which appears in its bounding walls. This condition of double valley extends from above Fort Snelling to the center of Saint Paul city. Related to the lower channel are terraces of limestone shingle within the valley at west Saint Paul, and potholes and loosened limestone blocks along the left wall of the channel, such as a gradually receding cataract would produce in making the channel; also an island of Saint Peter sandstone stands[7] midway in the valley of the Minnesota river, southwest quarter of section 33, Mendota, marking the place where such a receding cataract should have died out upon encountering the pre-Glacial channel of the Minnesota river. These phenomena are readily explained by the hypothesis that a cataract once receded from Saint Paul to and above Fort Snelling, even though they may not constitute indisputable proof of the same.

Further evidence appears from comparison of this double valley with that of other channels which are known to have been cut by recession of falls or rapids. Dr U. S. Grant, in studying the abandoned gorge at Minnehaha, emphasizes "the fact that the river did not cut its gorge of the same width as the channel in which it was flowing before wearing through the limestone."[8]

Whether the view which I present of the cutting of this double valley is accepted or not, it will be agreed by all who may study this part of the valley that it is swept clear of glacial drift and owes its present form and size to the Glacial river, a stream vastly greater than that which now meanders within its rocky walls. The deeper, narrower channel now serves as a valley for the Mississippi and Minnesota, with accompanying floodplain, swamps, and lakes. It will be conceded, too, I hope, that the river did not necessarily recede in volume as it was first drawn from the wide upper channel into the deeper, and therefore narrower, one.

According to the view which I have taken from the evidence already presented, the contrast in the valleys at the confluence of the Minnesota and Mississippi rivers is due directly to the size of the streams which made them. The valley from Saint Paul to and beyond Fort Snelling, which may be termed the River Warren valley, was made in a way very

[7] Upham: Op. cit., p. 81.
[8] Grant: Op. cit., p. 4.

similar in all respects to that of the Saint Anthony gorge, which indeed is a continuation of the former.

Beginning of the Saint Anthony Gorge

The erosion of Saint Anthony falls and gorge of the Mississippi began near the present Fort Snelling at a time when the Glacial river Warren (see figure 1) was at full volume. Winchell has estimated this beginning to have been at a much later time. He says:

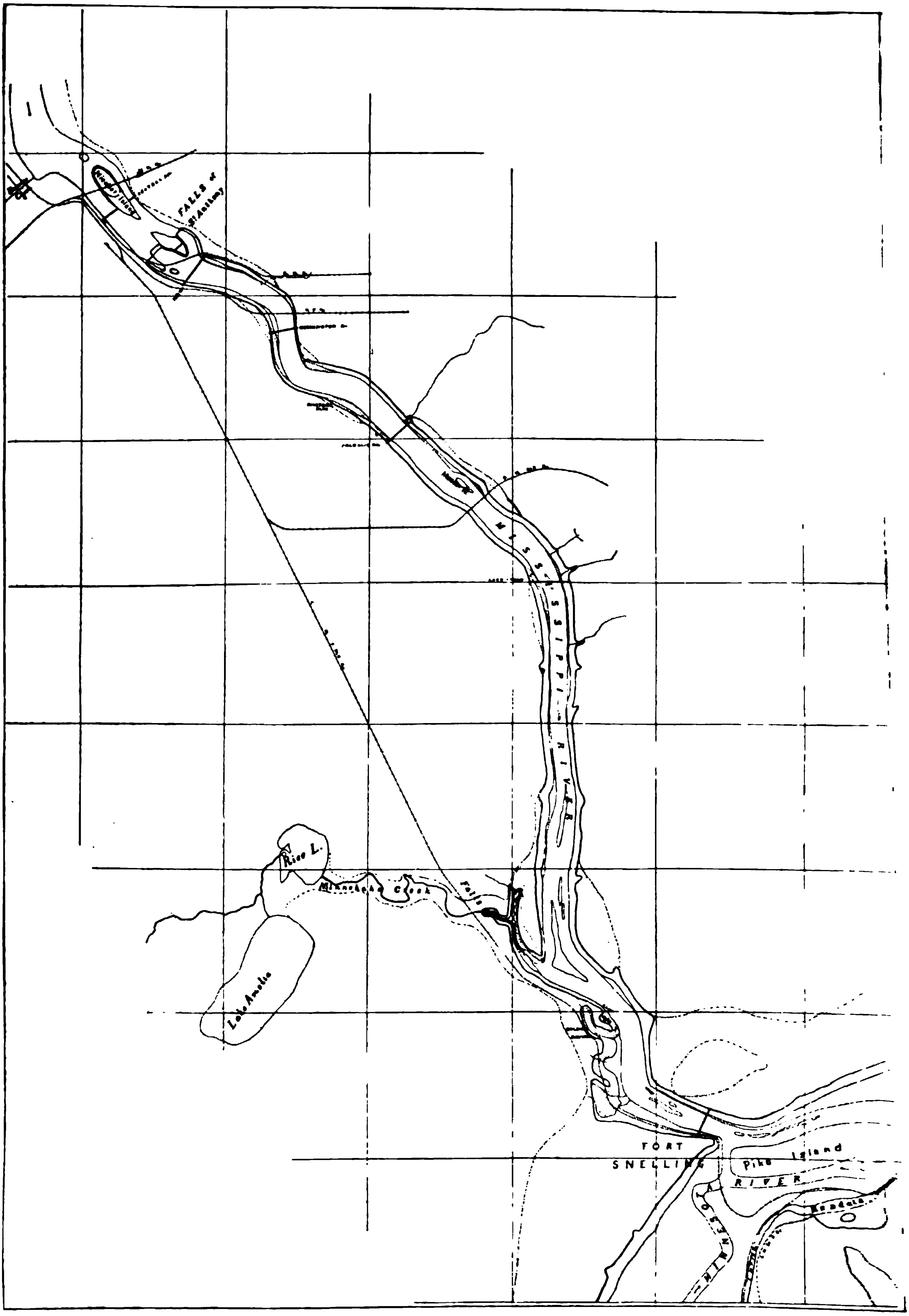
"There is reason to believe that the volume of the Mississippi was reduced to its modern stage before that of the Minnesota. When the Minnesota valley was finally relieved of the drainage from lake Agassiz, the falls of Saint Anthony may be said to have fairly entered upon the uniform recession which has been above considered."[9]

The Mississippi river undoubtedly did quite reduce to its modern stage while the river Warren was yet at full volume, and it may be assumed that such reduction in volume was affected by the final melting of the glaciers from the head of the Mississippi, as Winchell has above said; but that the Mississippi river was reduced to its modern stage before the recession of the falls began above Fort Snelling is not fully evident, and it is more than probable that the river Warren reduced to the Minnesota River stage long after the recession of the falls began. Besides the evidence which I have already presented, a study of the terraces within the gorge of the Mississippi will be given in a later paragraph to show when the falls began. The mouth of the gorge will be now described for the same purpose.

The gorge of the Mississippi at Fort Snelling is remarkably narrow, and its mouth appears as if truncated by the larger valley—the Minnesota (see plate 1). There is an abandoned channel or arm of the Glacial Mississippi, or, perhaps more strictly, of the river Warren, a half mile north and east of the mouth of the gorge. The land immediately on the west side of the gorge is also not high. The mouth of the gorge of the Mississippi is in fact far out in the original flat valley of the river Warren, on the upper end of what was evidently once an island.

From the position of the gorge's mouth it might be taken that the Mississippi had originally "plunged" by the shortest route over the wall of a preexisting Minnesota valley. Such a view appears to be the one entertained by Winchell. However, the reason for the narrowness and also for the particular location of the gorge's mouth may be explained only by the existence of a buried narrow pre-Glacial valley which could

[9] Winchell: Op. cit., p. 338.



MAP OF THE MISSISSIPPI RIVER FROM MINNEAPOLIS TO FORT SNELLING

Showing the recession of Saint Anthony falls

control the Mississippi's course at that place. The buried valley is evident at Mendota, opposite the mouth of the gorge, on the south side of the valley of the river Warren. An embayment lies in the valley's wall at Mendota. The back of the embayment is drift-covered or drift-filled, while the limestones and sandstone end abruptly on either side, as in case of a cross-cut buried valley. This buried valley may be a small branch from the buried pre-Glacial Minnesota lying south of Mendota, and it may have headed possibly a mile northwest of the present mouth of the gorge of the Mississippi. Such a valley transverse to the river Warren could have influenced that river's abandonment of the left channel and at the same time drawn the Mississippi into its present course.

In cutting the deeper channel, as before described, the river Warren followed obviously the right side of its older high and wide valley (see figure 2). The abandonment of the channel on the left side of the island opposite Fort Snelling is accounted for in a general way as due to the drawing of the stream to the deeper channel as it was made. In particular, however, one circumstance requires explanation, namely, the abandoned left channel beds upon the limestone ledge, as low as the crest of Saint Anthony falls would be at any stage. From the upper end this channel appears to be a course of the Mississippi abandoned just prior to the recession of Saint Anthony falls. At the lower end there is no channel nor alluvial beds and no evidence of a cataract where the Mississippi could have plunged from this channel into the deeper valley of the river Warren. The only explanation for that circumstance is that the river Warren for about a mile below the present Fort Snelling and the Mississippi for about a mile above that point may have settled in their valleys simultaneously and quickly as the oblique pre-Glacial valley at Mendota was encountered by a receding cataract of the former river, which would be first at a point about opposite the lower end of the left channel. Into this drift-filled and easily eroded course the rivers Warren and Mississippi could quickly settle, causing the abandonment of the left channel at once.

There appears therefore to have been no Saint Anthony falls at Fort Snelling, but rather the river settled into a narrow, easily eroded pre-Glacial valley at that place. The time of this event was while the river Warren had not yet cut its valley to near completion.

Early Stages of the Falls

Distinct evidence that there were falls or strong rapids on the Mississippi above the mouth of the gorge is found first about a mile upstream,

on the west side of the river. From the angle in the right wall of the gorge, in southeast quarter of section 20, township 28 north, range 23 west, for three-fourths of a mile to the north line of the section, there are scarps and terraces within the gorge which show quite unmistakably the former presence of falls and the character of the same. At Minnehaha other such evidence exists, as shown on the map, plate 1.

The best defined evidence is perhaps that near the north side of section 20, where there is an abandoned gorge which was once an arm of the Mississippi. This gorge does not appear in either name or form on any map known to me. Lately I have heard it called Soldier ravine. It is a clearly defined gorge about 800 feet long and 200 feet wide, flat bottomed and with steep slopes. It opens upon the right side of the main gorge at one end and ends blindly at the other. At its lower end it is like a "hanging valley" in relation to the main gorge. There is no stream or line of drainage now entering this gorge, although a steep gulch is cutting at the hanging end. This ravine and a roadway reveal that the floor of the gorge is made up for a depth of 5 to 15 feet of limestone blocks, with a few drift boulders resting on a very uneven or pockety surface of the Saint Peter sandstone. On the right and left, at the mouth of this gorge, are terraces about 10 feet above the floor, which consist likewise of blocks and boulders. These terraces have the same height as the bottom of the gorge at its head, namely, 35 to 40 feet below the top of the level limestone ledge. The head of the gorge has steep slopes like the sides. There appears to have been no filling in of the bottom such as to increase its original height.

Leading into the head of Soldier gorge, there is a channel 10 feet deep, 60 feet wide at the bottom and 100 feet over the top, which appears to represent the final stage of the stream which made the gorge. The channel is cut partly in drift, but mainly in the limestone. It runs now from the head of the gorge 200 feet back to the edge of the next cliff, where it is cut off. The channel is about one-half as wide as the gorge, and correspondingly the head of the gorge is narrowed or rounded. At earlier stages there was probably a larger stream that made Soldier gorge.

The evidence therefore indicates that Soldier gorge is an ancient abandoned branch of the Saint Anthony gorge, built by a receding cataract, the height of which was about 35 feet, measuring from the top of the limestone ledge to the bottom of the gorge. The gorge was abandoned somewhat gradually. The history of this gorge from beginning to end, I find, is involved in an interpretation of the bench which was an island on the east side of the gorge.

There was doubtless a fall on the arm of the river on the east of the

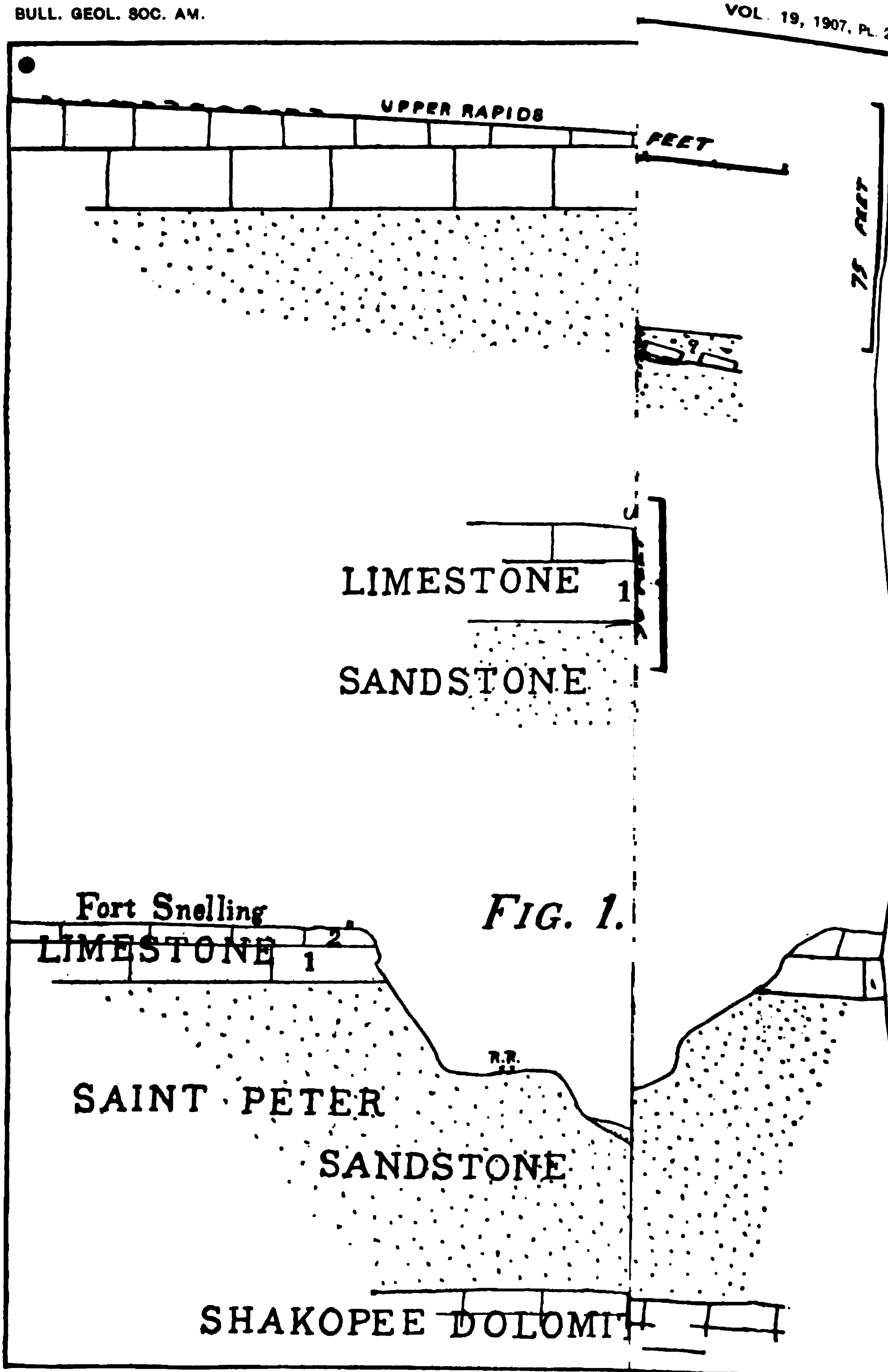


FIG. 1.

Figure 1 is a section across the Mississippi river near Fort Snelling

sland, and the recession of that one to a point above the other doubtless caused the abandoning of this, the shorter gorge. The bench or island did not merely divide the streams, the falls, and the gorges, but it, too, gradually uncovered and extended as the gorges were making. For example, on the east side of the island there is the remnant of the wall of a cataract and gorge. The crest of this cataract is level with the top of the island (figure 2, plate 2), and shows that the stream flowed across the north part of the bench, descended by a short rapids 10 feet, plunged then 25 feet, and then fell about 5 feet more in the next 50 yards. At that point the terrace is cut entirely off by the steep cliff made by lateral erosion by the Mississippi. Along the cliff a person can see the nearly longitudinal section of the entire rapids and fall. The front of this fall extends in straight line northeast to southwest and the stream ran southeasterly. Above the fall the river at that stage covered the top of the limestone bench, there being notably no deepened channel for the stream.

The east fall just described must represent a stage when Soldier gorge was half made, since the latter extends so much in front of the other. At the southwest corner of the island there is similar evidence of a cataract which relates to the terrace at that point, though it is not so clearly marked off as that of the east fall. It may, however, be mentioned as the west fall, contemporaneous with the east fall, indicating the stage to which Soldier gorge had then cut. The approach of the stream to this west fall is over the top of the limestone bench which later became the greater part of the island.

The island appears, in short, to have been produced by the dividing of the falls, and not the dividing of the falls due to an already existing island. The island at first was small and located at the brink of the falls. As the gorges on either side grew longer, the intervening bed of the stream was abandoned, thus extending the island. Finally this became the west bank of the river after Soldier gorge was abandoned. The island may have once extended some 500 feet farther north than the bench now does, that much of the cliff having since been cut away by the Mississippi at its present stage. If the island was so extended, the point at which the main fall and gorge intercepted the stream which was flowing to Soldier gorge might be some 750 feet north of the last named.

What I have called the east fall may in fact have been either a middle fall or for a time part of the main east fall. In either case the main east fall appears to have receded in a course which was well toward the present left wall of the gorge of the Mississippi here. The Soldier gorge was the shorter one and therefore had a more rapid descent to the junction than the other had. Exact comparison is, however, not practicable.

Southward from the mouth of Soldier gorge, there are other block-covered terraces skirting the limestone scarp for half a mile, which formed in part the sites of falls and in part the walls of consequent gorges alongside of falls. The Mississippi river at that early stage swept over the limestone bench west as well as east of the present railway track above the limestone scarp. The terraces here are all intercepted by the sandstone scarp which bounds the foot of the main gorge at no great distance from the limestone scarp, and they are crossed by three creeks, which have made deep ravines, so that their evidence is obscured. Their surface appears to have been covered by fewer and smaller limestone blocks than the more northern terraces were, and the Saint Peter sandstone, being thus less protected, has suffered more from subsequent erosion. The last terrace toward the south is notably little protected by limestone blocks. It is high, however, a few feet only from the top of the sandstone. The near-by limestone scarp on the north lacks the upper limestone bed. There appears to have been at this point a rapids or fall of 20 to 25 feet only, though the bed of the channel was 30 to 35 feet below where the top of the limestone would be if the limestone formation was entire here as it is elsewhere.

Briefly stated, the evidence shows us that the Saint Anthony falls at this early stage was as low as possible—that is, measuring from the top of the limestone which formed the crest, the falls were 35 to 40 feet to the bed of the river. The limestone is nearly 35 feet thick, so that the foot of the falls nearly coincides with the top of the Saint Peter sandstone. This sandstone was excavated 5 to 20 feet, this depth being filled again by blocks of limestone and debris. The descent from the foot of the fall in Soldier gorge is gradual, while that of the east fall is at first more rapid. From the evidence altogether, I estimate that the bed of the Mississippi at a distance from the fall, as at Fort Snelling, was 60 feet below the top of the limestone ledge at this stage. From this ledge now to the river is about 100 feet, and to the rock bottom of the gorge at Fort Snelling 175 feet, as shown in plate 2, figure 1.

THE GORGES AT MINNEHAHA FALLS

The Minnehaha gorge begins at the mouth of the creek, on the right side of the Mississippi river, about half a mile above Soldier gorge, just described, and two miles above Fort Snelling. It extends for half a mile (see map, plate 1), and then, as U. S. Grant has made known, it branches, each branch extending about one-eighth of a mile to an abrupt head. The gorge as a whole may be distinguished into three parts—the

gorge of Minnehaha creek above the junction, that below the junction, and the abandoned branch. The abandoned branch and that below the junction Grant interpreted as the work of a former arm of the Mississippi river, while the part of the Minnehaha gorge above the junction is exclusively the work of that creek. To a certain degree that interpretation is correct.

Minnehaha creek flows some 20 feet wide above and below the falls. At the falls it spreads out over a short rapids, and then plunges 60 feet into the gorge of its own making. The stream descends more than 40 feet from the base of the fall to its mouth. For 600 feet from the fall it flows in the part of the gorge which it alone has eroded. This Upper Minnehaha gorge is about 200 feet wide. At its head it forms nearly a semicircle, with the falls at its deepest part. The fall is thus apparently in a gorge much greater than its own width, though in fact the bottom of the gorge is only wide enough for the fall and the stream. The height of the falls is nearly the full depth of the gorge at its head, and fully half this depth is in the easily eroded Saint Peter sandstone. Deeper erosion is prevented mainly by the blocks of limestone which have fallen on the sides and bottom of the gorge and over which the stream rushes in its rapid descent from the foot of the fall. From the Upper gorge the stream enters what may be termed here the Lower Minnehaha gorge, through which it descends gradually to the Mississippi river.

The Upper and Lower gorges are alike in respect to narrowness at the bottom and rapid descent, and since the Upper gorge is crooked, its junction at nearly right angles with the Lower gorge is not an exceptional feature. The sole reason for distinguishing the Lower Minnehaha gorge from the Upper is because there is a third part which extends continuous in direction, width, and depth with the former. This branch of the gorge is now fenced as a deer park and may be designated the Deer Park gorge. It extends with slowly decreasing depth for about 1,000 feet from Minnehaha creek and ends blindly. Grant interpreted this and also a distinct channel which runs from above the end of the gorge to the Mississippi as the course of an ancient arm of the river, which they must be. The channel is flat bottomed, cut quite down to the limestone ledge, and is 300 to 400 feet wide, with an escarpment 10 to 15 feet high on either side. The left scarp runs from its north end, on the brink of the present gorge of the Mississippi, around in a curve back to the same near the mouth of Minnehaha creek. The right scarp coincides with the right wall of the Deer Park and Lower gorges.

That there was an island in the Mississippi dividing a main east arm from the longer west arm before Saint Anthony falls had receded to the

mouth of Minnehaha creek is therefore evident. That the Lower and Deer Park gorges were cut first by an arm of the river is also evident, and was done doubtless with a receding cataract at every stage. In the end of the Deer Park gorge was once a large cataract. There is no reason to question Grant's theory for the abandoning of the channel and gorge on the west side of the island, namely, that the cataract on the east side reached the head of the island first, and thus drew all the stream from the west channel. That the Deer Park gorge was made and abandoned at a time when the Upper Minnehaha gorge had been only begun is evident from comparison of distances reached by two gradually receding falls, Saint Anthony falls having receded 6 miles while Minnehaha falls receded one-eighth of a mile in the same time. The great size of the stream accounts for the rapid making of Deer Park gorge.

A feature which has been overlooked and which compels some revision of Grant's interpretation of the three parts of the gorge is that of a strong terrace within the Deer Park and Lower gorges. Considering the tract of land between the abandoned channel and gorge and the Mississippi river, the top of this tract is rather level and may be called the first terrace. It is bordered by a quite uniform scarp of the abandoned channel, as before described. Between this scarp and the gorge is the second terrace, resting on the limestone ledge. The descent from the limestone ledge to the bottom of Minnehaha gorge is in places a single scarp, but mostly there are two scarps with a distinct terrace, the third terrace between them. On the point of land between Minnehaha creek and the river the third terrace is well shown. Two large buildings of the Soldiers' Home stand on it, and their third-story windows are about on a level with the first story of buildings which are on the next higher terrace. The third terrace here is about 30 feet below the second and 75 feet above the river. Its top for 10 feet or more is made up of great blocks of limestone which rest on Saint Peter sandstone, all of which is well seen in the nearly vertical cliff next to the river.

The third terrace is a part of the original floor of the gorge, and the great angular limestone blocks on its top show it to have been made at the foot of receding falls. The same terrace extends, with one narrow interruption, up to a point nearly opposite the mouth of the Upper gorge. It extends again in the Deer Park gorge for short distances, and in the middle of the gorge's head a remnant lies at about 30 feet below the top of the limestone ledge. In one place midway in the Lower gorge a little lower terrace lies on the side of the third terrace.

From the position of these block-covered terraces I am led to think that the fall was 30 to 40 feet high, and that the gorge when abandoned by the

river was 30 feet deep at its head, 40 feet deep midway, and possibly 45 feet deep at the mouth. The original height of Minnehaha falls was 30 feet, whereas it is now 60 feet. Minnehaha creek has not only cut back its gorge one-eighth of a mile, but has deepened it, meanwhile eroding the bottom of the Lower gorge 40 to 70 feet deeper. The Deer Park gorge has also deepened. Two lines of drainage from near-by swampy tracts enter, one at each corner, at the head of this gorge, and those have changed the outline of the original crest of the old fall, as well as deepened the gorge.

The Lake Street Terraces and Fallscarp

For two miles above the mouth of Minnehaha creek the gorge of the Mississippi has a north to south course, with no ancient terraces within the gorge and narrow ones or none at the top. The limestone ledge on either cliff is surmounted by 20 to 40 feet of shales or by glacial drift. The shales appear to be continuous on the left side and to extend for the greater part along the right side. These, with the included crystalline limestone strata, are additional to that which the river encountered in the first 2 miles above Fort Snelling. The second 2 miles of Saint Anthony falls' retreat was peculiar in that respect, but as to the effect of that peculiarity we know little, since the long, straight gorge there is the only record of the river.

In the next, or fifth, mile from Fort Snelling the gorge curves toward the west. Here, as a person would expect, there are some terraces on the inner curve. As shown on the map (plate 1), a high terrace runs across the north half of section 5. This terrace is 15 to 20 feet above the top of the limestone ledge and is marked off by a well defined scarp on the west side. The stream appears to have made an island on the east side of the terrace. The height of the terrace rather indicates that it was abandoned by the river a long time before Saint Anthony falls reached that part of the gorge. I compare it to the high terrace at Minnehaha creek. Also, near the bottom of the gorge, there is a long terrace, with a remnant of a fallscarp at its northwestern end, and above this there was formerly a sloping approach, or upper rapids, where a stone quarry now yawns. From notes taken over 10 years ago, when the quarry was small, I am able to describe that part also. Saint Anthony falls left a well preserved record of its course, including upper rapids, fallscarp, lower rapids, and river bed, here within an eighth of a mile above the west end of Lake Street bridge—that is, the southwest corner of section 32. A profile of the fall is shown in plate 2, figure 3.

The scarp, which once formed the west end of the fall here, stands

transverse to the right wall of the gorge. Its crest is 30 paces long, measured from the bank above it to the cliff by which it is now cut off. Upstream from this remnant of the falls formerly extended a sloping triangular area of the upper rapids. It rose over 15 feet in the 120 paces from the top of the falls back to the point where it was cut off by the convergence of the bank above and the cliff below it. Formerly many small river shells were found under the limestone shingle, there being a foot of such debris between the soil and the limestone floor, so that these as well as the slope and position of the terrace proved it to have once been the river bed above the falls. The descent of the rapids, 15 feet in 120 paces, extended from the top of the upper limestone to its base.

The crest of the fall rested on the top of the lower limestone. The scarp of the fall is now covered in part by the quarry dump, but it was formerly regular, presenting a low cliff bordered by a talus slope, in all 20 feet high—that is, reaching from the top to the bottom of the lower limestone. Originally this appears to have been a vertical fall of 20 feet. From the foot of that scarp a steep slope, covered by limestone blocks and debris on Saint Peter sandstone, runs with a gradient of 1 in 5 for 100 feet. It changes then to a gradient of 1 in 10, decreasing gradually to 1 in 100; so that the bed of the river at 100 paces from the fall was 75 feet below the top of the upper limestone—that is, upper rapids—and 60 feet below the crest of the falls. The heights here are: upper rapids, 15 feet; fall and cataract, 40 feet; lower rapids, 20 feet.

The terrace below the fallscarp consists of limestone blocks 1 foot to 10 feet in diameter and boulders, filling over the very unevenly eroded surface of Saint Peter sandstone from 5 to 15 feet deep. The terrace is 50 to 75 feet wide now and 40 to 20 feet above the river. At 350 feet from the fallscarp the terrace has been disturbed by the building of Lake Street bridge, but remains intact close beyond that obstacle. There it is 20 feet above the present river, has nearly as little gradient as the river, and extends 60 paces wide for 400 paces. Another part of the same is seen a little farther along, beyond a 10-foot lower terrace which suddenly widens back to the foot of the bluff here, after it has paralleled the main terrace in a narrow strip for a long distance.

The falls at this stage cut the gorge here originally 30 or more feet deeper than it did at and below Minnehaha. (Compare figures 2 and 3, plate 2.)

Other Terraces

In the last 3 miles up to the present Saint Anthony falls each turn in the river's gorge preserves some record in the form of terraces and scarps

within the gorge. Likewise terraces remain above the sides of the gorge. The retreat of the falls, and hence the direction of the gorge, appears to have been influenced somewhat by the direction of the joints in the limestone beds, so that the course of the river preceding the falls' recession is not exactly followed by the gorge.

Most of the terraces have been disturbed more or less by stone quarries and the like, doubtless some of them before Winchell began his study of the falls. There remains clearly defined nearly all of the terrace which occurred 10 to 15 feet above the limestone ledge, in several places, and some part at least of another, 0 to 5 feet above the limestone ledge, which accompanied the former generally. River shells occur in gravels along the scarp between those two terraces.

Within the gorge terraces occur in several places. On the left wall of the gorge, at Meeker island, a narrow but characteristic block-covered terrace begins at 55 feet below the top of the limestone ledge, 35 feet above the normal river level, and descends with decreasing gradient 15 feet in 100 yards, and then for another 100 yards maintains about the same elevation, 20 feet above the river.

In Riverside park, at the north end of Twenty-seventh avenue south, on the right wall of the gorge, is to be seen the extreme end of a fallscarp and below it a rapidly expanding terrace. The present wall of the gorge cuts obliquely across this scarp, so that all or nearly all of the original rapids above the fallscarp had been cut away even before a stone quarry was begun here. In the quarry 4 feet of hard crystalline limestone strata and interlaminated shale of bed number 3 appears above the 14 feet of the regular upper limestone (bed number 2) and the lower limestone. Since the crest of the fall appears to have been at the top of the lower limestone, there would have been 18 feet descent in the rapids above the fall. The old fallscarp is not well preserved in form, but its top is seen 60 feet above the present river bed, and it has a gradient of 25 feet in the distance of 60 feet. Thence a descent of 20 feet in 200 paces is followed by a gradient which parallels that of the present river for another 100 paces. The terrace in this part becomes 100 feet wide and then narrow again. Quarry dumps now conceal the narrow part for a long distance, but I remember that it was continuous with the block-covered strip which lies 15 to 20 feet above the river's normal level at the Franklin Avenue bridge.

The entire descent in falls and rapids at Riverside was thus 60 feet, the river flowing thence 15 feet above the present normal level. The now remaining terrace displays on its edge next to the river a fine profile of the very irregularly eroded surface of Saint Peter sandstone, covered 10

to 20 feet deep by debris, including limestone blocks 1 to 25 feet square and 1 to 6 feet thick. These blocks are almost exclusively from the lower limestone.

At the old Chevertown steamboat landing, between the ends of Pleasant and Delaware streets, and on the boulevard, on the left side of the gorge, another remnant of the fallscarp is preserved. The nearly right-angled turn in the wall of the gorge preserves the edge of an upper rapids and the fallscarp. These evidence that here also rapids descended 15 feet over the upper limestone to the fall. The fall was 25 feet high, measured from its crest at the top of the lower limestone. Below that scarp the block-covered river bed, now a terrace, slopes from west to east and is 45 or 50 feet below the top of the limestone ledge and 25 feet above the river at normal stage. The terrace runs some 300 yards to where it is scarcely 15 feet above the river. A terrace which is from 10 to 5 feet lower borders it on the south side.

A sloping block-covered terrace runs under Washington Avenue bridge, on the right side of the gorge, but the works of man have changed it too much for the present purpose; also, on the left end of Tenth Avenue bridge, the "east side flats" once presented doubtless a good record, but it has been defaced by early quarrying and late grading. It can be seen, however, that the limestone ledge had been eroded or glaciated here, so that 5 feet of the upper limestone was lacking. The block-covered terrace began at the base of the lower limestone and sloped in some way down to about 10 feet above the present level of the river in a fourth of a mile. The height here was probably, of the upper rapids, 10 feet; of the falls, 20 feet; of the lower rapids, 20 feet; total, 50 feet.

This last terrace is so close below the position[10] at which the falls stood when they were seen by Father Hennepin in A. D. 1680 as to represent practically the same stage.

The Nicollet Island Rapids

Before considering the Saint Anthony falls proper, which N. H. Winchell has described quite fully, I wish to call attention to what may be called the Nicollet Island rapids, to which due attention has not been paid heretofore.

The limestone ledge which formed the crest of Saint Anthony falls, and which is practically horizontal from Fort Snelling to the falls, shows a rise upstream above the falls. "At the falls it amounts to about an inch in 100 feet; it increases soon to 3 or 4 inches in 100 feet, and at Central avenue it is about 5 feet in 100 feet." [11]

[10] Winchell: Op. cit., p. 336 and plate Y.
[11] Winchell: Op. cit., p. 291.

As a result of this pronounced dip with the stream, the limestone ledge which forms the crest of the fall rises above the bed of the river opposite the lower end of Nicollet island, and at the upper end of the island it is wholly above the river, the Saint Peter sandstone reaching some 20 feet above the water level. The river channel on either side of Nicollet island has been cut through the limestone formation and partly into the Saint Peter sandstone. This condition extends up the river a fourth of a mile beyond Nicollet island, where, as Winchell describes it, a drift-filled pre-Glacial valley is met. The rise of the limestone is toward the side of that valley.

Briefly stated, the Mississippi river flows along the pre-Glacial valley for some miles in a southerly direction to the mouth of Bassett creek. The old valley continues in the direction of the creek, southwesterly, while the river turns southeasterly over the side of that old valley. The Mississippi river, at an early stage, must have encountered the limestone which bordered the old valley, since the ledge was there at the present 820-foot contour line. There is indeed evidence of thickly deposited silts to indicate that the Mississippi river and Bassett creek were impounded back of the limestone ledge for a time.

The river channel would encounter the limestone on its upturned edge, and a rapids would soon result from such a barrier. As the river cut its way obliquely through the limestone the rapids must *pari passu* descend the river. At an early stage the river flowed in a rapids in part over the now high and rocky upper end of Nicollet island, while in its last natural stage (1856) I learn that the rapids began opposite the lower end of the island, reaching thence to the falls.

There has been evidently this Nicollet Island rapids descending the river, cutting the limestone ledge at one edge, while Saint Anthony falls ascended the river, cutting the ledge at the other. In its last stage Saint Anthony falls has entered the reach of the Nicollet Island rapids. The last stage is therefore very different from earlier ones.

Saint Anthony Falls

To the description of Saint Anthony falls I need add but little. This fact should be noted, however, that the last stage of the falls differs as compared to earlier stages in that the lower limestone remains alone, the upper limestone having been cut away under the river by the Nicollet Island rapids, into which the falls had receded. An artificial dam above the falls now raises the water to about the level of the upper limestone—that is, to 795 feet above tide—which appears to have been the height of

the river above the falls in its earlier stages. Excepting for the artifi dam above the falls, the river there might be 15 feet lower than it wa earlier stages. Winchell had estimated that the limestone formation (15 feet from Fort Snelling to the falls, but I am not able to find by u the contour map of the U. S. Geological Survey that such is the c The lowering of the river above the present falls much rather began v the joining of the Nicollet Island rapids and the rapids above the f and the consequent reducing of the upper limestone. This lowe would be gradual. Very probably Father Hennepin saw the fall Saint Anthony (1680) before the river had cut all the upper limes from its bed, and possibly the change was not complete when Ca (1766) saw it. The increased rate of recession of the falls, too, s Carver's time, as calculated so nicely by Professor N. H. Winchell, be due to the changed condition of the falls and rapids.

With the bed of the river resting on the top of the *lower* limes only, the last stage of the falls began. The manner of recession has come a matter of historic record. While since 1871 the front of the has been protected by an "apron," yet the recession had been well obse before that time.[12] I have seen two breaks in the crest which occurred in the last few years. "It is not so much the excavation at foot of the falls that causes the recession as the excavation of the s stone just below the lime rock by water that enters natural joints in rock and comes in contact with the crumbling sandrock, causing dislo ment and final downthrow of large blocks."[13] Recently caves for under the limestone and enlarged until the ledge fell. Blocks once thi down were farther lowered by eroding of the sandstone from under t gradually, so that a block-covered rapids extended from the foot of falls to where the blocks had been brought as low as the underminin them could proceed.

Conclusion

As already stated, the Minnesota-Mississippi valley from above Snelling to Saint Paul is not a pre-Glacial valley, but a Glacial and Glacial one, which was cut to its maximum depth by the river Wa in the same manner as the Saint Anthony gorge was made by the M sippi river. The recession of Saint Anthony falls may be taken as ha begun in a fall or rapid of the river Warren over 5 or 6 miles below confluence of the Minnesota and Mississippi rivers. That fall e above the confluence on the river Warren in the Minnesota valley.

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[12] See Annual Report Chief of Engineers to the Secretary of War for 1870, p. 27

[13] Winchell: Op. cit., p. 340.

recession of Saint Anthony falls proper is a continuation of the former on the Mississippi above the confluence.

During the entire recession two events are presumed necessarily to have influenced the volume of the rivers: One was the melting away of the glacier from the head of the Mississippi (see figure 1), presumably causing a marked reduction in volume of the river from its Glacial to its modern stage. The other was the breaking of the ice-barrier and opening of drainage to the northward, by which lake Agassiz was drawn off and the river Warren reduced to the Minnesota river stage.

Regarding the reduction of the Mississippi river, a double system of terraces and scarps is evident above the walls of the Saint Anthony gorge in several places.[14] These belong undoubtedly to the river at stages preceding the making of the gorge. They are interrupted by the widening of the gorge, and thus are not continuously traceable, but yet appear to represent two distinct stages of the river. The lower of the two lies distinctly within the upper, so that a person may readily interpret them as representing respectively the modern stage and the Glacial stage of the Mississippi. The higher or Glacial Mississippi terrace extends from Nicollet island to and continuous with the terrace and scarp of the river Warren, as shown in plate 1. The lower terrace coincides with the present river channel above the falls and is evident for 6 miles, or to the mouth of Minnehaha creek. I have not distinguished it beyond the Soldier ravine. The change in the Mississippi river consequent to the melting of the glacier from its head may be referred to the stage of the river to which the making of the Soldier gorge belonged—that is, when the falls were 1½ miles above Fort Snelling.

The reduction of the river Warren may also be correlated with a stage of the recession of Saint Anthony falls and the making of the gorge. The rock gorge of the Mississippi at Fort Snelling is 75 feet deep below the level of the river (figure 1, plate 2), and the valley thence to Saint Paul is the same. The falls did not excavate to that depth, as is shown by the evidence seen in terraces and also by comparison with the gorge above Lake Street bridge at lock and dam number 2, where the river was found to run on the sandrock bottom of the gorge. The bottom of the gorge at Fort Snelling and thence to Saint Paul is to be considered as a refilled valley. The time of the maximum depth may well be considered as that of the last days of the river Warren. The time of maximum depth of the gorge should also correlate with the time of greatest height

[14] A still higher and very distinct terrace runs parallel to the east side of the gorge, but it belongs to the time of glacial occupation preceding the forming of the Mississippi river proper, and is not considered here.

of the falls at the temporary head of the gorge. The stages indicated by terraces and fallscarps show the height of Saint Anthony falls and rapids together to have been as follows: At Fort Snelling, no falls; at 2 miles the descent was 40 feet; at about 4 miles, 75 feet; at 6 miles, 55 feet;[15] at 8 miles, 50 feet. The time of the reduction of the river Warren may therefore be correlated with the falls when at Lake Street bridge, or about half way from the mouth to the present head of the gorge.

Regarding the rate of recession, it can not be said to have been uniform. For the 5 miles below Fort Snelling I have no data from which to calculate directly, but from above that point the first mile of the gorge of the Mississippi was evidently taken up by the river very quickly, by reason of a pre-Glacial valley there. Thence for a mile—that is, to Minnehaha creek—the evidence of the waterfall is seen. It evidently reached in depth only to the base of the limestones, where the stream, rebounding from the limestone blocks which had fallen, could surge back and undermine the scarp by washing away the friable sandstone. The limestones are jointed at intervals of 10 to 40 feet, and this facilitated the caving off of blocks. That both limestones were thrown down together is evident, since the upper is mingled with the lower in the debris now found in the terraces. The lower limestone predominates, however, and this is evidently because the upper is not so thick and, moreover, had been reduced by erosion in the rapids, which extended 50 or 100 feet beyond the fallscarp.

At the Lake Street, or 4-mile, stage the rate of recession appears to have been slower than at the 2-mile stage. An upper rapids extended back over 300 feet, indicating time for erosion of the upper limestone. The caving off from the front of the fallscarp was evidently slow. The blocks, which cover the terrace below the fall, are almost exclusively from the lower limestone, testifying that the upper limestone was all eroded preceding the falling of blocks. The recession of the fall involved evidently first the complete removal of the close-jointed upper limestone; second, the caving down of the lower limestone in blocks, because of water entering its joints and undermining the sandstone; and next the great blocks forming a lower rapids were slowly undermined, sinking to the bed of the river. This manner of recession at the Lake Street stage appears to have continued to the Tenth Avenue bridge, or 8-mile stage, where the falls entered the Nicollet Island rapids.

In its last stage the falls entered the Nicollet Island rapids and made doubtless a greatly accelerated retreat, because the upper limestone was

[15] Sixty feet high at Riverside park includes 4 feet above the top of the second limestone.

wanting, as already described. The rate at this stage is the one which Winchell very nicely calculated. He believed that the same rate applied to the making of the entire gorge, which it evidently does not.

Very possibly the falls were only entering the Nicollet Island rapids at the time when Hennepin and Carver saw them, and the upper limestone was not all gone from the fallscarp. Winchell calculated the recession of the falls from the time when Hennepin saw them, A. D. 1680, to that of Carver, 1766, to be 412 feet, or 4.79 feet per year, and from 1766 to 1856 to be 606 feet, or 6.73 feet per year. The increase of 40 per cent in the rate of the second period over the first indicates, I think, that the falls were in transition stage. In that case also the first must be an increased rate over that of stages preceding the entrance of the falls into the Nicollet Island rapids. Since 5 feet, or one-third, is lacking from the upper limestone at Tenth Avenue bridge, it seems probable that the same was only half eroded away at the time of Father Hennepin's visit. We may therefore assume four periods of accelerated recession, of which the two just cited as calculated by Winchell are the last. If we accordingly discount the rate of the third, 4.79 feet per year, by 40 per cent twice, we may find the probable rate of recession (2.44 feet per year) previous to the entrance of the falls into the Nicollet Island rapids.

While the rate of recession of the falls as taken by Winchell is twice too great, the length of recession which he takes for the time since the falling of the river Warren and ending of the ice-barrier in the north is twice too long. At the time of that event he supposed the falls to have begun at Fort Snelling, while most probably they were half way along in retreat, or at the Lake Street stage. From there to Tenth avenue the recession was fairly uniform. Taking, then, one-half the rate and one-half the length, the number of years, as calculated by Winchell for the event of the reduction of the river Warren, is not necessarily changed. Eight or ten thousand years may have elapsed while the last 4 miles of the gorge were making.

Probably no less an interval elapsed while the preceding 4 miles were making from above Fort Snelling to Lake street, though in this case the rate was not evidently uniform, and calculation of years from distance divided by a supposed rate would be very uncertain. The recession was at first comparatively rapid, but the falls during that interval were increasing in height, tending toward slower recession. The volume of the stream may have been reduced much below that which it was later, and this would tend toward slow recession. Here, also, for a part of the distance, perhaps a mile, as said, the limestone was augmented by crystalline limestone and shales. Of the effect of all this we have no good record

for a distance of over 2 miles. The fall possibly approached the cascade type, as seen in the Minnehaha falls now, where the limestone stands in an overhanging ledge from which the stream makes a clear leap to the bottom of the gorge. The recession of Minnehaha falls depends on the weathering down of the shaly contact between the Saint Peter sandstone and the limestone. The limestone then scales off in small pieces, from the base upward, and the sandstone washes slowly away, so that a ledge remains upon which a pony can be ridden under the falls.

The gorge from Saint Paul to Fort Snelling is still more uncertain. In a more general comparison it may be said that we have represented in these gorges three periods or units. From Saint Paul (representing locally the beginning of ice-retreat) to the Soldier gorge above Fort Snelling is one unit; from the Soldier gorge (representing the time of the glaciers' retreat from the head of the Mississippi) to the Lake Street stage is a second unit; from Lake street (representing the time of falling off of lake Agassiz and river Warren) to the present is a third unit. If the last is 10,000 years, the other two may be each no less, giving 20,000 years as the duration of the river Warren and 30,000 years as the lapse of time since the glaciers decamped from Fort Snelling.

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WIND EROSION IN THE PLATEAU COUNTRY[1]

BY WHITMAN CROSS

(Read before the Society December 31, 1908)

CONTENTS

INTRODUCTION

The agency of the wind in the degradation of land areas is generally recognized, in the abstract, as comparable with that of water, excepting as to the magnitude of the work done. It is evident that air currents transport dust and sand particles, and the abrasive action of a sand blast is in kind similar to the erosive effect of a debris-laden flood, but due recognition of the role played by the wind in the erosion of special areas is perhaps not so commonly accorded. Recent observations convince me that the Great Plateau country of the western United States is one of the provinces in which the effective degrading or denuding agency of the wind has not been fully appreciated. The facts on which this belief rests will be presented in the order in which they were observed.

The first thing to be considered will be certain apparently eolian soils occurring about the mountains in Colorado; then follows evidence that the wind-blown material came from the Plateau country. A district in Utah where wind work has clearly been done will be described and facts given tending to show the quantitative measure of the work accomplished.

EOLIAN SOIL IN COLORADO

Adjacent to the San Juan mountains of Colorado, and particularly in the larger river systems, there are notable gravel plains at various elevations between 50 and 400 feet above the adjacent streams of today. The higher and older of these plains cover many square miles in the drainage

[1] Published by permission of the Director of the U. S. Geological Survey. Manuscript received by the Secretary of the Society February 3, 1908.

system of the San Juan river and clearly antedate the recent glaciation of the mountains. A discussion of these gravel terraces and plains, as to their origin and relations, has been published by Mr Howe[2] and myself, and the only feature of present interest is a peculiar fine, reddish, sandy soil which occurs almost everywhere as a mantle to the gravel deposits. The invariable character of this soil and its presence on terraces of different elevations attracted the attention of A. C. Spencer, who, in 1896, was my assistant in the survey of the La Plata quadrangle, Colorado, and was particularly charged with the study of Quaternary problems. Mr Spencer believed this red soil to be of eolian origin, and the correctness of that opinion has become more and more evident with extended observations.

The thickness of the deposit in question is commonly several inches, while in some places it exceeds 2 feet. The red soil has seldom been observed on other surfaces than the gravel plains and terraces. Viewing it as of eolian origin, it is natural to suppose that the sand first lodging between gravel grains and pebbles became a soil permitting a vegetable growth, which in turn served to catch and hold more sand. The light, wind-blown particles do not seem to have accumulated on inclined surfaces, which would be more exposed to the degrading action of wind or water than the level plains. It is, however, quite possible, as Mr Spencer has suggested to me, that eolian soil may exist on certain old mountain slopes covered by forest growth and changed in color by the action of humus acids. Observations directly bearing on this have not been made.

This red soil seems wonderfully constant in character, and it is believed that its average mechanical constitution is represented by the subjoined analysis of a sample collected by myself from a terrace adjacent to the La Plata river, at a point in New Mexico very near the Colorado line. At this locality the soil was more than 1 foot in thickness, and the specimen obtained did not appear to have been disturbed by the plow. Through the courtesy of Dr Milton Whitney, in charge of the Bureau of Soils, U. S. Department of Agriculture, Mr Lyman J. Briggs made the following mechanical analysis of this red soil from La Plata valley, New Mexico:

No.	Organic matter.	Gravel, 2 millimeters to 1 millimeter.	Coarse sand, 1 to 0.5 millimeter.	Medium sand, 0.5 to 0.25 millimeter.	Fine sand, 0.25 to 0.1 millimeter.	Very fine sand, 0.1 to 0.05 millimeter.	Silt, 0.05 to 0.005 millimeter.	Clay, 0.005 to 0.0001 millimeter.
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
78642......	0.79	1.74	5.66	3.52	9.72	38.00	28.40	12.50

[2] Ernest Howe and Whitman Cross: Glacial phenomena of the San Juan mountains, Colorado. Bull. Geol. Soc. Am., vol. 17, 1906, pp. 251-274.

This analysis shows that more than 88 per cent of the sample consists of particles less than 0.25 millimeter in diameter. According to the investigations by Udden[3] as to size of grains in wind deposits, about 86 per cent of dune sand measures between one-half millimeter and one-eighth millimeter in diameter; from 70 to 95 per cent of "lee sand" is between one-fourth millimeter and one-sixteenth millimeter in diameter, and in atmospheric dust a great majority of the particles measure between one-eighth millimeter and one-thirty-second millimeter. Certain volcanic dust deposits examined by Udden gave results upon diametrical analysis quite near that of the red soil. So far as the mechanical constitution of the red soil is concerned, it may well be chiefly atmospheric dust derived from a great distance.

The geographic situation of the supposed eolian soil deposits on the eastern border of the Plateau province, in conjunction with the prevalence of strong winds from the west during much of the year, serves to indicate the probable derivation of this fine sand from the desert area of the plateaus. Opportunity to trace the deposits to the general region of their apparent source was given me in 1905, during a reconnaissance from Mancos, Colorado, to Moab, in Grand River valley, Utah.[4] The route of travel led over the broad arid plain between Montezuma creek and Dolores river, which is called the Great Sage plain on the Hayden topographic map of Colorado and eastern Utah. This plain is underlain by the Dakota Cretaceous sandstone, with remnants here and there of the soft Mancos shale resting on that sandstone.

That a red sandy soil as a coating is not in fact peculiar to the gravel plains already discussed is shown by the occurrence of the same material at many points on the Great Sage plain, covering sandstone or shale, as the case may be. It is held in place by the same kinds of desert vegetation which grow on it in the zone nearer the San Juan mountains. No greater thickness of the sand was found on the broad plateau than on the terraces of the La Plata and other tributaries of the San Juan river to the east.

The method of transportation of the red sand or soil is visibly demonstrated to the traveler riding over the Great Sage plain on a hot summer's day, for on every hand he sees huge columns of dust, rising as whirlwinds, sweep over the arid waste. This dust is thus borne to higher strata of the atmosphere, where it is caught by strong currents and carried to varying distances. The prevalent winds of the present time blow from

[3] J. A. Udden: The mechanical composition of wind deposits. Augustana Library publication no. 1, Rock Island, Illinois, 1898.

[4] Whitman Cross: Stratigraphic results of a reconnaissance in western Colorado and eastern Utah. Journal of Geology, vol. xv, 1907, pp. 634-679.

the northwest, and it seems reasonable to suppose that they have long had the same direction. While the wind transportation of dust and fine sand is thus demonstrated on the plain, the whole process of deflation, of which the transportation is a part, may be studied in the area lying between the Abajo and La Sal mountains. Here also may be found some measure of the denudation accomplished.

The Plateau Country East of Grand River, Utah

If the reader will refer to the Hayden map of this border zone between Colorado and Utah,[5] or to the Abajo and La Sal topographic sheets of the U. S. Geological Survey, he will see that the Great Sage plain, floored by the Dakota sandstone, forms the divide between these two mountain groups, wraps around the northern base of the Abajo mountains, and ends in flat-topped ridges reaching out toward the Grand River canyon, but a few miles distant. The scarp by which the plain is terminated on the west and north is the uppermost of a series of cliffs marking the outcrops of the harder, more resistant members of the middle Mesozoic section which have been cut through by Grand river. The same rocks also form the floor of terraces extending back from these scarps to varying distances. It is this type of topography which characterizes the Plateau country adjacent to the larger canyons, not so overpowering here as in the Colorado Canyon district farther south, yet meriting the glowing descriptions given of it by Newberry[6] and Powell.[7] The principal sandstones seen in scarps or terrace floors, as the case may be, occur at various horizons within the White Cliff (Jurassic) or Vermilion Cliff (Triassic) groups of Powell, or, in the terminology of the southwestern Colorado stratigraphic column, respectively the La Plata and Dolores sandstones. Between the La Plata and Dakota sandstones occurs the McElmo (Jurassic) formation, some 500 or 600 feet thick, made up of friable sandstones, sandy marls, and clays, so destructible that the formation usually presents a steep debris-covered slope below the Dakota rim of the upper plateau. All these formations are prevailingly reddish in color, varying from light pink to the strong deep red of the Vermilion Cliff sandstone. The White Cliff sandstone forms the "Orange cliffs" of this region, and in many

[5] U. S. Geological and Geographic Survey of the Territories, etc. Geological and Geographic Atlas of Colorado and portions of adjacent territory, by F. V. Hayden, 1881, sheets xiv and xv.

[6] J. S. Newberry: Report of expedition from Santa Fe, New Mexico, to the junction of the Grand and Green rivers of the Great Colorado of the West, in 1859. Washington, 1876, pp. 93-100.

[7] J. W. Powell: Exploration of the Colorado river of the West and its tributaries. Washington, 1875.

FIGURE 1.—VIEW IN DRY VALLEY, UTAH, BETWEEN ABAJO AND LA SAL MOUNTAINS

To show the level floor and desert vegetation: an isolated hill of Jurassic sandstone with characteristic deflation sculpture, and the distant plateau border of the valley made of the same sandstone. Photograph by Cross, 1905

FIGURE 2.—CASA COLORADO, DRY VALLEY, UTAH

A hill of white Jurassic sandstone with alcoves such as are common in the district. Photograph by W. H. Jackson

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places its color has led to its mistaken correlation with the Vermilion Cliff sandstone.

DEFLATION IN DRY VALLEY

The area between Grand River, the La Sal, and the Abajo Mountain groups has few deep canyons. The principal one is that named "Cañon Colorado" by Newberry, who descended it to Grand river. The name is also used on the Hayden map, but is omitted from the Survey sheets. This canyon derives its principal water supply from the slopes of the La Sal mountains, but its largest drainage area is a broad basin, appropriately named Dry valley. This valley, with its several branches, occupies the greater part of the area between the La Sal and Abajo mountains. It approaches to within a few miles of the slopes of the Abajo group, but now receives no water from that source, since the streams heading on the northern slope curve either to the east to join Montezuma creek, a tributary of San Juan river, or west directly toward the Colorado.

At the head of Dry valley three of its branches cut back into the Great Sage plain as narrow streamless canyons several hundred feet in depth, shown on the map; but the greater part of the basin is an arid expanse with low ridges of gray or light red sandstone. The main floor is at or very near the top of the lower division of the White Cliff sandstone and approximately 1,000 feet below the level of the Great Sage plain.

The general character of the valley floor and of the sandstone ridges between its branches is shown by figure 1, plate 3. While there may be local ravines cut into solid rock, where cloud-burst floods have done their work, there is, in the portions of the valley I saw, no continuous watercourse through which debris is now transported, even by flood water.

The sandstone ridges, such as those of figure 1, exhibit many evidences of rather rapid wasting through the usual disintegration due to the atmospheric conditions of desert lands. The sandstone is normally a very massive, fine-grained, even-textured rock, friable and crumbling under the blow of a hammer. In many places a dust-like coating is on the more protected surfaces, while miniature talus heaps of fine sand are found below some exposed faces. In many places thin coats of brown "desert varnish" preserve the exterior, while the interior is rotten or cavernous.

The topographic forms presented by the La Plata sandstone of Dry valley are almost invariably of rounded contours such as suggest to the trained eye the sculpturing of wind erosion. Peale records in these words the impression produced on him on seeing this district from the summits of the La Sal group: "The beds appear to be horizontal and in many places have cave-like holes worn by rain and wind."[8]

[8] A. C. Peale: U. S. Geological and Geographic Survey of the Territories, etc., Ninth Annual Report for 1875, p. 66.

Holmes received similar impressions on viewing Dry valley from the Abajo peaks.[9] The "cave-like holes" noted by Peale form, in fact, one of the most peculiar characteristics of Dry valley. It is common to find the exposures of the upper La Plata sandstone sculptured with huge recesses or alcoves, both in the more exposed ends of ridges and in long lines of rounded cliffs. Figure 2, plate 3, represents the "Casa Colorado," as named by Newberry, an isolated remnant of sandstone near the upper end of Dry valley. From the colored sketch of this point given in Newberry's report,[10] it seems certain that a photograph by W. H. Jackson, in the files of the Geological Survey, represents the same sandstone monument, and this photograph is reproduced here as figure 2. The character of the alcoves is here well illustrated and needs no further description.

Such erosional remnants are not uncommon in Dry valley. One observed by our party seems, from its position, to be the Casa Colorado of the Hayden topographic map. This is shown in figure 1, plate 4, and it is manifestly not the one so called by Newberry. In this case the alcoves are lacking, but the rounded faces suggest the modeling of wind action.

Another interesting illustration of these peculiar cave-like forms is afforded by Looking-glass rock, near the southwest base of the La Sal mountains, of which a view is given in figure 2, plate 4. In this case a huge alcove on the southern face actually penetrates the rear wall, and there is a large opening through it. The scale of the whole is shown by the minute figures of two men standing in the window at the rear and by the mule on the plain in front of the alcove.

At the time of visit the walls of this alcove had a thin coat or crust of disintegrated sandstone, crumbling at a touch. This is clearly the common meal of disintegration, due largely to the great diurnal change of temperature characterizing the region, which is particularly effective upon just such rocks as the La Plata sandstone. That the alcove is not wholly the result of excessive local decay of that sort is plain from the coarse debris upon the floor, representing the breaking up of huge scales of rock detached *en masse* from the ceiling. The fragments are in process of disintegration just as are the walls. The swirling eddies of fierce blasts sweep this loose dust and sand out of the alcoves.

Our observations were not extended enough to demonstrate fully the process by which these alcoves in the La Plata sandstone have been made, but it seems to me that it must have been chiefly through the disintegra-

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[9] W. H. Holmes: U. S. Geological and Geographic Survey of the Territories, etc., Tenth Annual Report for 1876, p. 191.

[10] J. S. Newberry: Report of expedition from Santa Fe, New Mexico, to the junction of the Grand and Green rivers of the Great Colorado of the West, in 1859. Washington, 1876, plate vi.

FIGURE 1.—HILL OF WHITE JURASSIC SANDSTONE, DRY VALLEY, UTAH

Shows characteristic wind-sculptured forms of the region. Photograph by Cross, 1905

FIGURE 2.—LOOKING-GLASS ROCK, DRY VALLEY, UTAH

A remnant of white Jurassic sandstone with a large alcove which penetrates the rear wall. The size of the opening indicated by the figures of two men. Photograph by Cross, 1905

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tion of the sandstone and the removal of debris by wind. To this must be added occasional corrasion by sand-laden blasts. When an alcove has been formed its growth may be greatly accelerated through the scaling off of rock flakes from roof and side walls.

Aside from the larger alcoves just discussed, the faces of La Plata sandstone are in numerous localities characterized by small pits, which are in some places most abundant in certain strata and are hence arranged with some regularity; but in other localities they are abundant and very irregularly arranged in the massive cross-bedded rock. These cavities are common features of crumbling rocks in desert lands and have been abundantly illustrated by Walther and others. In figure 2, plate 3, and figures 1 and 2, plate 4, may be seen areas where such small pits are plentiful.

As processes now in operation, the decay of rocks in an arid region and the action of the wind in the removal of waste are more strikingly illustrated in Dry valley than in any other district I have examined, but the extent of the work thus performed in the past is most plainly indicated by other facts than those thus far recited. The floor of Dry valley, like that shown in figure 1, plate 3, is strewn with subangular or partially rounded fragments of impure chert, indurated sandstone, conglomerate, and bluish gray sandy limestone. Many fragments are from 1 to 3 feet in diameter and a few are much larger. They are not by any means sufficiently abundant to form a connected layer, but several lie close together in many places. It is rare to find an interval of as much as 200 yards between fragments. No part of the valley floor traversed by various members of our party was found to be free from such large fragments, nor were they seen in stream beds, as if accumulated by torrents. The hard cherty or dense siliceous rock fragments were most abundant. Many blocks are polished and grooved by sand-laden wind. Few are rounded sufficiently to be compared to water-transported boulders.

As to the origin of these masses, it is evident that they are not derived from the La Sal or Abajo mountains by recent glacial transport. The former small valley glaciers of both groups ended at or very near the debouchure of the mountain gulches on the surrounding plains, as was ascertained by morainal and other evidence at several localities. The debris can not, indeed, be plausibly referred to a mountain source by any means or at any time, for the reason that the hard intrusive porphyries of the numerous laccoliths and sills of these mountains are not represented in this debris. Gravel plains coated by small, well rounded pebbles, among which are many of porphyry, do extend a short distance into the southwest head of Dry valley, and these are probably outwash plains of the recent glaciers or interglacial terraces comparable to some of those

about the San Juan mountains. Such gravel deposits are distinct from the coarser debris scattered over the entire valley.

The rocks occurring in these large fragments are all of sedimentary origin, and familiarity with the section of the region soon suggests their source. The conglomerate mentioned as a component of this debris is relatively rare; and it is unmistakably derived from the Dakota sandstone. It is mainly composed of small chert pebbles of various colors and shades, and is typical of the basal conglomerate of the Dakota as known all through Colorado and in other states. The conglomerate was found to be particularly well developed at the base of the Dakota in the southern arm of Dry valley, called "Cold Spring cañon" on the Hayden map.

The rusty indurated sandstone, which is more abundant than the conglomerate in the valley debris, is likewise probably derived largely from the Dakota. A cementation of the Dakota sandstone by silica and iron hydroxide is much more common than in the McElmo and La Plata formations, and many fragments of the valley floor are very similar to strata visible in the Dakota sections about the valley.

The cherty fragments and the limestone were not so readily referred to their proper horizon, but an examination of the upper surface of certain La Plata ridges, like those of figure 1, plate 3, showed an almost continuous deposit of fragments; and exposures of the zone between the McElmo and La Plata formations revealed the presence, just above the La Plata, of a stratum several feet thick made up chiefly of impure cherty material. Where best exposed, on the road from Moab to Monticello, as it descends from the divide north of Canes spring, this stratum is made up of a confused brecciated mass of dense siliceous rock with a sandy calcareous cement. The limestone was not seen in place, but is believed to occur at or very near the horizon of cherty material. No fossils were found in it, though repeatedly looked for.

My conception as to the origin of these blocks scattered over Dry valley is that they are the residue of the harder rocks in the section of sedimentary beds out of which the valley has been carved mainly by *deflation*, using this term as proposed by Walther[11] for wind transportation. They appear to have been let down gradually through the disintegration and transport of the soft clays, shales, and sandstones of the Dakota, McElmo, and upper La Plata formations.

The fine desquamation products of sandstone and shale in Dry valley have of course been subject to some degree of transportation by water. The features of the valley already mentioned indicate, however, notable aridity and rarity of floods. The wash of occasional rains must transport

[11] J. Walther: Das Gesetz der Wüstenbildung, p. 83.

the rock flour down the slopes, but it is to be remembered that when the mud has dried out, wind is free to undo much of the work accomplished by water. Our observations did not suggest the presence of a large amount of detritus in process of slow transportation by wash.

The character and size of the residual blocks, the vertical distance through which the Dakota fragments have descended—about 1,000 feet—the scattering of debris so evenly alike over valley floor and intervening ridges, seem to me to harmonize with the view that wind has been the dominant agency in the removal of the sediments below the Dakota level, and may be throughout the work in the same degree that its power is evidently far more efficacious than that of water at the present time.

That water has played an important part in the topographic history in producing an initial drainage system of canyons penetrating below the Dakota level is perhaps suggested by the sharp canyons at the head of Dry valley, "Cañon Pintado" of Newberry, Cold Spring canyon, and two others, unnamed, which are shown on the Hayden map. Whether or not one postulates a system of such canyons originating under more humid climatic conditions than those of today, wind action alone would seem competent to remove the rock waste of the ridges between gorges and at the same time leave behind the blocks which have been described.

I was not familiar with the details of Walther's[12] elaborate discussions of denudation in desert areas when the visit to Dry valley was made. The facts observed forced me to the independent conclusion above presented; but the student of Walther's treatise will see much in what has been narrated confirming the views of the German geologist as to the great part played by the wind in the erosion of desert provinces. Especial interest attaches to such confirmation in this case, since Walther has expressed the belief that deflation has been a very important process in the sculpturing of many vast amphitheaters of the Grand canyon above the Esplanade.[13] His view was based upon general considerations and personal impressions and lacks the support of detailed facts of observation.

Application to Plateau Province

The observations here recorded were made during a hurried journey, when attention was particularly directed to problems quite different from those of denudation. Important evidence bearing on the subject of this paper may have been overlooked, and hence too broad generalization must be avoided; but it is well known that the Vermilion Cliff and White Cliff

[12] J. Walther: Das Gesetz der Wüstenbildung.

[13] Johannes Walther: Die nordamerikanischen Wüsten. Verhandl. Gessellschaft für Erdkunde zu Berlin, band xix, 1892, p. 52.

sandstones, with soft strata above and below them, are among the most widely distributed formations on either side of the Colorado river. The climatic conditions of the high plains near Grand river are common to much of the Plateau country; hence it seems evident that if deflation has been effective in the area between the Abajo and La Sal mountains it must be assumed to have done important work in many other districts.

The stupendous erosion of the Plateau country represented by the Colorado canyon and its tributaries has been the subject of much discussion. It has seemed to some physiographers that such a gigantic task could not have been accomplished under existing climatic conditions, always assuming water to have been the only transporting agency. With this idea, recourse has been had, notably by Dutton,[14] to the hypothesis that a more humid climate prevailed during the principal epoch of canyon erosion. In a recent discussion of this question by Davis[15] it is held that even under existing conditions the topography of the Grand Canyon district is adequately explained as due to water transport of land waste. In no discussion of this question is the process of deflation treated as of importance. Davis refers to a suggestion made to him "by a correspondent well versed in the topography of arid regions" (Walther ?), that wind action has been an important agency in producing the huge amphitheaters of the Colorado canyon, but is unable to accept the suggestion in the case of those forms "inasmuch as their slopes are always developed in accordance with lines of gravitative action, and not in sympathy with the flowing lines characteristic of the bottom of an air current." He admits that "the wind is a powerful agent in regions where vegetation is as scanty as it is on the barren walls of the Colorado canyon."[16] Davis does not discuss the effect of deflation in the localities where the wind is admitted to have been "a powerful agent."

In all probability the relative importance of wind and water transportation in the Plateau country has not been discussed because satisfactory criteria for distinguishing them and for measuring the wind work have not been recognized. It is hoped that the foregoing brief statement of observed facts, together with the interpretation which has been advanced as seemingly most reasonable, may serve to draw the attention of special students to an important and hitherto almost wholly neglected line of investigation in the wonderful province of Plateau and Canyon adjacent to the Colorado river.

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[14] C. E. Dutton: Tertiary history of the Grand Canyon district. Monograph ii, U. S. Geological Survey, 1880.

[15] W. M. Davis: An excursion to the Grand canyon of the Colorado. Bull. Mus. Comp. Zool., vol. xxxviii, 1901, pp. 187-192.

[16] W M. Davis: An excursion to the Plateau province of Utah and Arizona. Ibid., vol. xlii, 1903, p. 34.

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ROCK-FLOOR OF INTERMONT PLAINS OF THE ARID REGION[1]

BY CHARLES R. KEYES

(Read before the Society December 30, 1907)

CONTENTS

INTRODUCTORY

The geologic structure of the arid region comprising the Great basin of western America and the northern part of the Mexican tableland is supposed to be characteristic of that anomalous class of geotectonics known as the Basin Range, or Block Mountain, type. Its distinctive feature is commonly considered as the product of normal faulting on a prodigious

[1] Manuscript received by the Secretary of the Society January 11, 1908.

scale. Lately, the long accepted opinions regarding the Basin Range structure have been brought seriously into question. As a result a new interest in the subject has been kindled.

That the tectonics of the regions mentioned have never received the careful consideration that the natural advantages for study would seem to demand is due partly to a singular notion which has prevailed from the first, that these regions present structures of great simplicity and hence require little detailed examination.

Physiographically the dominant feature of the Great basin and the Mexican tableland is the plain. The most conspicuous features are the mountains. These, like isolated, lofty piles, rise abruptly above the even, sea-like plains as do volcanic isles out of the ocean. Areally the highlands occupy much the less space. One-fifth of the surface of the region is mountain; the plains cover four-fifths.

To the casual observer the smooth surface of the plains appears to have few exposures of bedrock and to be everywhere deeply mantled by loose, and for the most part rather coarse, rock-waste. The mountains, on the other hand, are bare and free of vegetation, permitting their structure to be displayed as nowhere else in the world outside of arid countries. The geologic structure of these regions has been in the past largely inferred from the parts protruding above the level of the plains, while those portions beneath that level have been generally regarded as inaccessible and have been almost altogether neglected.

The general tectonics of the two regions under consideration and the Basin Range structures need not be taken into account now, for the reason that they will receive special attention in another place. In the present connection only the characters of the substructure of the plains is to be considered.

Foundation of the Arid Plains

Definition of "Bolson"

Although views regarding the geologic structure of the Great Basin region and of the Mexican tableland have differed more or less in details, there has been a consensus of opinion that the mountains are being worn down to build up the intervening plains, and that finally the former will be all carried down into the latter. A common opinion is the one advanced by Le Conte, which regards the mountains as the elevated margins of huge tilted blocks and the plains the depressed and buried portions of the same blocks.[2] Starting with this conception, it is an easy step to the

[2] American Journal of Science (3), vol. xxxviii, 1889, p. 259; also Elements Geology, 5th edition, 1904, p. 242.

conclusion that the plains are all deeply covered by mountain waste, even to depths of thousands of feet. At first glance on the ground such an explanation of the phenomenon presented seems to leave little room for refutation.

So firmly has this notion prevailed that Hill, in 1900, in describing the physiographical features of the Greater Texas region (including New Mexico and Colorado east of the Rio Grande), gave it technical fixity by calling the intermont plains in the New Mexican part of the district "*bolsons,*" deriving the name from the Spanish title for these plains, which signifies a purse, or basin without outlet. Hill's definition is essentially as follows:

"These plains, or basins, as they are sometimes called, are largely structural in origin. Bolsons are generally floored with loose, unconsolidated sediments derived from the higher peripheral region. Along the margins of these plains are talus hills and fans of boulders and other wash deposits brought down by the mountain freshets. The sediments of some of the bolsons may be of lacustrine origin. . . . It is essential, in both the geographic and the geologic discussion, to bear in mind the distinction between bolson plains and plateau plains. The plateau plains and the mountains are genetically related, the strata composing the one being bent onto or flexed out of the other. The bolson plains, on the other hand, are newer and later topographic features, consisting of structural valleys between mountains or plateau plains, which have been partially filled with debris derived from the adjacent eminences. The plateau plains are usually destructional stratum plains. The bolson plains are constructional detritus plains filling old structural troughs."

The types which Hill selected to illustrate his definition and which he specifically described were the Hueco, Sandoval (Estancia plains), and the Jornada del Muerto basins, all of which are in eastern New Mexico. Some minor basins farther to the southward were also briefly mentioned.

JORNADA DEL MUERTO AS THE TYPE

About the time of the appearance of the Hill memoir I was engaged in making geologic inquiries into the underground water supplies of the region occupied by the three great bolsons mentioned. These investigations were undertaken for three different railways, and were soon afterward supplemented by similar inquiries for several mining companies. This work was not hurried geological reconnaissance, but careful investigation extending over a period of several years with residence in the region. Its results were measurable quantities, demanding expression in feet and dollars. Some of the more important of these results have been already published in a memoir on the "Underground water conditions of

the Jornada del Muerto, New Mexico,"[3] "Geotectonics of the Estancia plains,"[4] and other shorter papers, to which reference may be made for many details bearing upon the subjects here discussed.

As early as 1903 I endeavored to show,[5] in a brief article on the "Geological structure of New Mexican bolson plains," that (1), so far at least as the Jornada del Muerto and Estancia plains were concerned, Hill's interpretations were wholly incorrect; (2) instead of being structural valleys deeply covered by mountain waste, the rock surface of the two basins referred to was worn out on the beveled edges of Cretacic and Carbonic strata, representing a total thickness of more than 10,000 feet; and (3), for the most part, the rock-floor of these plains was covered by only a thin veneer instead of by great thicknesses of loose materials.

A geological cross-section of the Jornada del Muerto presents something of the structure represented below (figure 1), the length of the section being about 30 miles. To all appearances the plain is a simple, very shallow syncline, the ends of which are clearly visible in the lofty Sierra de

FIGURE 1.—*Beveled Rock-floor of the Jornada del Muerto, New Mexico*

los Caballos and the Sierra San Andreas at a distance of a score of miles from the railway which traverses the middle of the plain. From the train the surface of the plain, as far as eye can reach, appears floored by gravels and coarse mountain waste; in reality it is covered by soft, porous loam and sands, and so even is the surface that the railway grade in a distance of 60 miles scarcely cuts or fills the inequalities.

Closer examination of the ground and a comparison of the drill-well records, shallow dug-well records, and the few outcrops clearly show that the beds do not lie in a simple syncline of which the mountains are the upper protruding limbs. The strata are disposed at much higher angles than the general dips of the simple synclinal trough would require. Moreover, near the mountains, especially on the west side of the plain, is a belt 3 to 4 miles wide where the surface, so level when viewed from a distance, is found to be trenched by intricately ramifying canyons, often several hundreds of feet deep. The geologic formations are here everywhere well exposed. While the general slope of the plain toward its center is only from 2 to 3 degrees, the dips of the strata are frequently as high as 30

[3] U. S. Geological Survey, Water Supply and Irrigation Paper, no. 123, 1905, 42 pages.
[4] Journal of Geology, vol. xvi, 1908.
[5] American Journal of Science (4), vol. xv, 1903, pp. 207-210.

degrees in the same directions and in places they are even vertical. On the beveled edges of the steeply inclined beds the plains-gravels and clays are laid down, and also broad sheets of basaltic lavas, the latter spreading out from numerous small cones.

What is most surprising is the fact that the detrital materials covering the plains have such small depth. Over at least two-thirds of the Jornada the rock-floor is frequently exposed, protruding through only a few feet of soil. There do not appear to be the least grounds for assuming that this plain is deeply filled with debris on account of the Rio Grande having formerly occupied the middle of the basin, as has been recently stated by Lee.[6] None of the well records examined gave any indication of a broad detritus-filled valley; but they do show that the Carbonic limestones and Cretacic sandstones occur only short distances beneath the surface, at least from the west side nearly to the base of the San Andreas range on the east. At the south end of the Jornada there are Tertiary deposits having a thickness of several hundreds of feet. These also appear to be slightly beveled. As these deposits consist of soft, though well stratified, materials, it is manifest that in the various well borings they have not been differentiated from the later surface debris washed down from the peripheral highlands.

Similar Tertiary deposits of great thickness are known to exist below Albuquerque, above Albuquerque, and at other points on the upper Rio Grande. It is more than likely that in all of these localities there has been a failure to discriminate between the older and younger of the soft deposits, thereby ascribing an unusual thickness to the latter. In the light of recent investigation it is probable that all of the reported data tending to prove the great thickness of the surface deposits of the bolson plains of this regions will have to be examined anew.

The original types of the bolson plain, as that term has been given technical geographic significance, are thus clearly destructional plains with very thin covering, instead of constructional plains with very thick detrital deposits. If the name is to be retained in geographic literature with a distinct or special significance, it should be only in the widely accepted sense to which the Spanish people have been accustomed. The American adaptation is not only ill chosen, but defined under misapprehension. The latter usage of the name should be abandoned.

SUBSTRUCTURE OF THE ESTANCIA PLAINS

The Estancia valley is similar to the Jornada del Muerto, adjoins it on the north, and extends 100 miles in that direction to the city of Santa

[6] U. S. Geological Survey, Water Supply and Irrigation Paper, no. 188, 1907, p. 21.

Fe. Deep stream-erosion across the valley and many wells indicate clearly the character and thin cover of the rock-floor.

Although the surface of these plains is very smooth and is apparently everywhere covered by mountain wash, the thickness of the soft mantle is rarely over 100 feet. The indurated rocks which form the foundation of the plains are often inclined at high angles and are evenly beveled. A typical cross-section is shown near the Hagan coal camp (Uña de Gato),

FIGURE 2.—*Beveled Plains—Surface of Cretacic Sandstones*

on the east side of the Sandia range, and is represented below (figure 2). The height represented by the section is about 600 feet. The outcrops of the section extend almost continuously for a distance of 20 miles along the Arroyo San Pedro. A similar section of upturned and beveled Cretacic strata is exposed near the town of Los Cerrillos. In the vicinity the same phenomenon is repeated hundreds of times.

LAS VEGAS OF NEVADA

"The Meadows" of southern Nevada constitute a vast even plain bordered by lofty mountains. Eastward from the town of Las Vegas extends a long arm of these plains, which, as it passes between two ranges and joins Meadow valley to the east, is 6 to 8 miles wide. In this arm of the plain the geologic structure is well displayed (figure 3).

FIGURE 3.—*Geologic Cross-section of the Vegas Range, Nevada*

The attitude of the rocks and the relations of the beveled rock-floor to the overlying wash deposits are more clearly shown than immediately to the east or to the west. Still farther to the eastward, in Meadow valley, where there is a perennial stream occupying its middle, a narrow and deep canyon has been cut in the old bolson. Tertiary deposits are in-

volved, and both these and Paleozoic rocks are standing at high angles, with the tops everywhere evenly beveled.

INTER-RELATIONSHIPS OF INTERMONT PLAINS OF CALIFORNIA

Mountain-locked desert plains of southeastern California frequently have their rock-floors covered by only a few feet of soil and debris. Along the Mohave river, northeast of Barstow and elsewhere, artificial excavations have disclosed soft Tertiary strata standing in edge and completely planed off. At the American borax mines, north of Daggett, the following section is shown (figure 4):

FIGURE 4.—*Vertical Tertiary Beds, near Daggett, California*

The plain in which the mines are located is very even and without conspicuous outcrops of bedrock. At the mine shafts the truncated edges of the beds over a considerable area protrude through the thin surface mantle. Similar conditions obtain 10 miles to the northeastward, near the mines belonging to the Pacific Coast Borax Company.

In other plains of the vicinity the rock-floor appears to be made up of thick andesitic and other lava flows which have been tilted and beveled.

There is a hypsometric relationship among some of the intermont plains of California that is not so apparent anywhere else in western America; yet similar relations are known to exist in many parts of western and southern Arizona and in New Mexico. The great difference in elevation at which adjoining plains stand above sealevel is very suggestive. An east and west profile (figure 5) of the country between the Sierra Nevada and the California-Nevada state line is transverse to the axes of both the valleys and the mountain ranges. Its character suggests frequent and profound faulting; but faulting alone does not appear to offer the full explanation of the unequal altitudes of a given series of desert plains. The question is raised whether there does not exist a more or less perfect independence of neighboring plains in their development, planation, and surface modification under desert influences. The probability of every intermont plain in the arid region attaining a level that is

its own and that has no genetic relation with any other plain is a deduction that is in strict accord with the known effects of certain plain-forming desert agencies. If we can ascribe to the wind the chief erosive influence or gradation process, there is no baselevel to attain, as in the case of normal erosion by water. At the same time there can be the

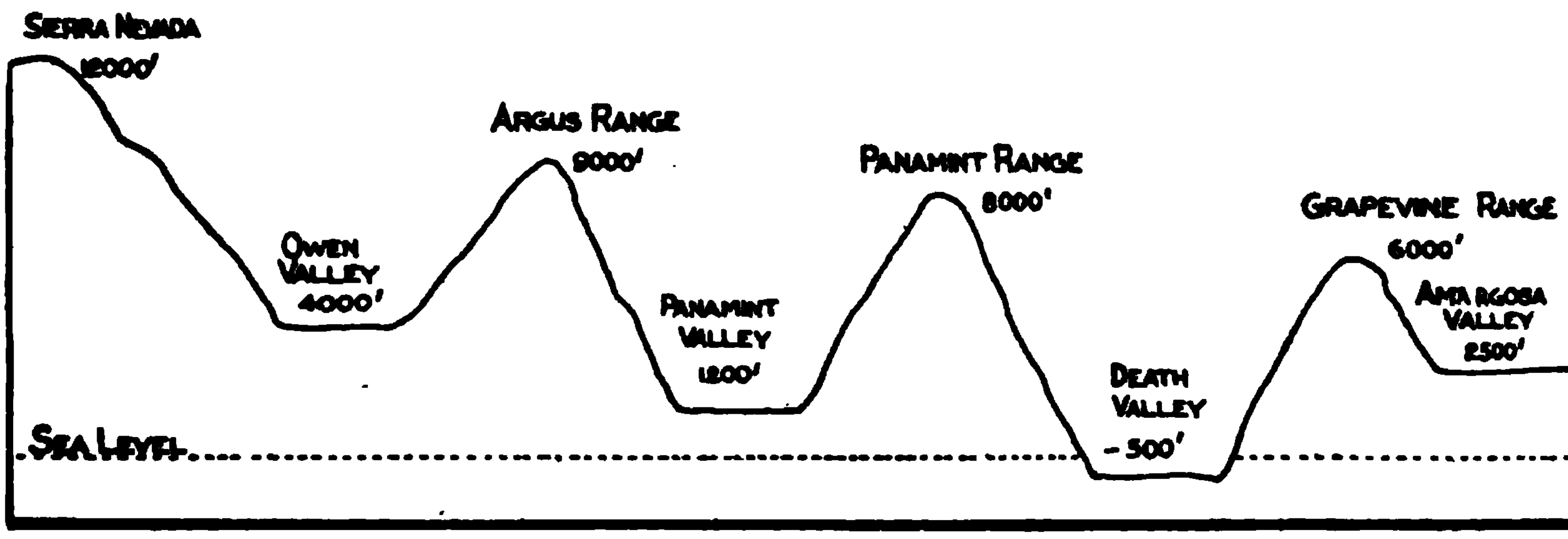

Figure 5.—*Profile of Death Valley Region, California*

numerous local levelings in a much broken region like the Great basin, or a general leveling of a vast undisturbed area, as in the case of the interior tableland of South Africa. This, however, is a theme for special discussion and more extended consideration than can be given it here.

COURSE OF THE COLORADO RIVER

After leaving its Grand canyon, the Colorado river still flows nearly to its mouth in a deep valley which has been corraded through a line of mountain-locked basins. This part of the river's course has been frequently pointed to as an illustration of a region throughout which great thicknesses of recent sediments have been deposited over the intermont plains.[7]

Deep-well records are given as the chief evidence supporting the opinion that the valleys are floored with recent debris to great depths. The uncertainty of these records has been already pointed out. Lee states in no uncertain terms that—

> "Over a large part of the Southwest, extending from New Mexico to the Pacific ocean, detrital material fills the low places generally and transforms into broad detrital plains districts which might otherwise have very uneven surfaces. In Arizona, where the writer has observed the deposits most widely, the detritus occupies the lowlands to the south and west of the Colorado plateau."

It may be that the long basin extending southward from the mouth of the Virgin river, and which the author just quoted calls the Detrital-

[7] Bulletin of the Geological Society of America, vol. 17, 1906, p. 275.

Sacramento valley, is deeply underlain with recent gravels. My own observations in the same valley north of the Colorado river immediately lead me to raise the question as to how much of the soft deposits occupying the valley are those of Tertiary lake beds and how much those of later wash materials. The solution of this problem might very greatly modify the various views expressed. It is known that a few miles north of the Colorado river, on the west side of the south-flowing Virgin, in the canyons of Muddy river and the Meadow wash, very thick Tertiary beds are exposed. Were one to drill a well on the top of the mesa or smooth, even surface of the intermont plain, he might penetrate soft deposits considerably more than a thousand feet, and yet less than a hundred feet would be recent wash gravels.

The Lower Colorado River region has been regarded as lately covered by the sea. According to this notion, all of the plains must have been formed by depositions in a quiet sea that was thickly studded with islands—the present isolated mountains. Such an hypothesis must have very much stronger evidences to support it than it now has before it can be even considered as a possible explanation of the phenomena presented.

The Colorado river is not a typical watercourse of the arid region. Being a large, perennial, through-flowing stream, its work and evolution are those of a river of the humid regions. It rises in the highest "Rockies" and reaches the sea. Of the same class of great streams are the Rio Grande, the Rio Pecos, and the Canadian river of New Mexico. Typical geographic development in an arid climate goes on without the drainage regularly reaching the sea. A very clear distinction must therefore be made between the materials composing the waste mantle in and near the valleys of these streams and those commonly met with in the intermont or bolson plain.

Lee[8] notes that the Colorado river "in selecting its course seems to have shown little consideration for the easiest lines of erosion. It has disregarded mountain and valley alike. From casual observation it would seem to have chosen about the roughest course possible." If we consider this river as having cut its channel down from the surface of an old baseleveled plain, Lee's inferences might be sustained. If, however, the stream has followed the lowest line of short intermont plains, an entirely different interpretation must be held. If the intermont plains are thinly floored with wash deposits and are mainly the product of general leveling without baseleveling, the explanation of the great channelway through short rock-bound canyons connecting one open plain with another is not difficult. The case is identical with those of the valleys of

[8] Loc. cit., p. 277.

the other great through-flowing streams of the region. The course of the Colorado river needs to be considered in the light of its development under conditions of an arid climate rather than that of a normal humid one.

SURFACE OF THE COLORADO PLATEAU

For the most part the surface of the great Colorado plateau in northern Arizona is a stratum plain composed of hard Carbonic limestones. Around the margins on all sides younger strata are found. It has been generally regarded that this surface is essentially a plain of denudation that was formed at baselevel. Whatever may have been the original character of this surface, it appears now that it has been profoundly wind-swept. It may be that it was almost entirely leveled by eolian action.

The thick resistant limestones of Carbonic age that usually constitute the surface of the great dome are not broken by faults, as in the regions surrounding. The limestone is the same which forms the foundation of many of the tilted mountain blocks beyond the confines of the plateau. The latter is thus not subject to the influences of differential erosion, whether of wind or water.

The rock-floor of this great plateau is in many areas scarcely covered by sufficient soil to support a scant vegetation. The Santa Fe railway west of Gallup traverses many miles of level country, into which soft materials had to be brought for long distances to construct a grade that would obviate rockwork. The canyon Diablo is excavated out of a rock stratum plain as if graven with a gigantic chisel.

The rock-floor of the plain of the Colorado plateau is often bared for scores of miles. The consideration of its origin from the viewpoint of leveling without baseleveling is fraught with unusual interest.

BOLSONS OF NORTHERN MEXICO

Many of the intermont plains of the northern part of the central tableland of Mexico have very shallow soil coverings. In all observed cases the rock-floors are an even plain beveling much disturbed strata. Many of the bolsons through which the Mexican Central railway passes display at many points the rock-floor under only a few inches or a few feet of loam and debris.

On the west side of the Sierra Madre, McGee[9] has called attention to certain peculiarities of the rock-floor of the vast plain of Sonora. He says:

[9] Bulletin of the Geological Society of America, vol. 8, 1897, p. 90.

"At first sight the Sonoran district appears to be one of half-buried mountains, with broad alluvial plains rising far up their flanks, and so strong is this impression on one fresh from humid lands that he finds it difficult to trust his senses when he perceives that much of the valley-plain area is not alluvium, but planed rock similar to or identical with that constituting the mountains. To the student of geomorphy this is the striking characteristic of the Sonoran region—the mountains rise from the plains, but both mountain and plain (in large part) are out of the same rocks. The valley interiors and the lowlands are, indeed, built of the torrent-laid debris, yet most of the valley area carries but a veneer of alluvium so thin that it may be shifted by a single great storm. Classed by surface, one-fifth of the area of the Sonoran district, outside of the Sierra and its foothills, is mountain, four-fifths plain; but of the plain something like one-half, or two-fifths of the entire area, is planed rock, leaving only a like fraction of thick alluvium. This relation seems hardly credible. During the first expedition it was noted with surprise that the horseshoes beat on the planed granite and schist or other hard rocks in traversing the plains 3 or 5 miles from the mountains rising sharply from the same plains without intervening foothills; it was only after observing this phenomenon on both sides of different ranges and all around several buttes that the relation was generalized, and then the generalization seemed so far inconsistent with facts in other districts that it was stated only with caution even in conversation."

The author just quoted ascribes to sheetflood erosion the origin of the rock-floors of the Sonoran plains. The activity of wind as an accompanying planation agent is not suggested. The main facts, however, are the singular character, the shallowness, and the great extent of the rock-floors of the northern Mexican intermont plains.

DEBRIS OF THE BOLSON PLAINS

The soft mantle covering the intermont plains of the arid region is usually described as made up of gravels. The plains deposits are, however, in large part fine clays or loams. There are some sands; but on the whole there is comparatively little real gravel and coarse rock material. The latter appears mainly in the paths of the torrential drainage-ways debouching from the mountains and on the piedmont slopes, but seldom extends very far out into the plains area proper.

There are two or three aspects of the plains debris that perhaps tend to give a false impression regarding its composition. The arroyos leading from the mountains have high gradients; their waters, whenever there are any, are invariably torrential in character; the fans produced at the mouths of the canyons are mainly made up of coarse waste. To the traveler who is accustomed only to the geologic phenomena of the humid climate the natural inference is that the coarse materials from the high peripheral belt are carried down to level up the low plain.

The other misleading point is that pebbles do actually appear to occur everywhere over the plains. This aspect is almost always very deceptive. Gravel and small boulders are to be found scattered over the higher slopes of nearly all of the intermont valley plains. That they give to the loams the appearance of gravel beds is due to the fact that the winds constantly blow away the fine materials. The pebbles left behind serve as a protection to further wind action until a floodsheet or torrent disturbs the coarse surface layer of small stones. It is not uncommon to find areas several acres in extent covered with small angular stones as closely and as evenly set as mosaics. The pebbles may be only one deep; below is fine porous loam, into which man and beast in crossing sinks as into newly fallen snow. Turned up by the plow, the most barren tract of this kind may prove to be the finest of loamy soil.

The almost gravelless plains detritus and the thin mantle over a beveled rock-floor observed in the arid regions make one's notions derived from experiences in humid lands undergo radical modification.

Significance of a thinly mantled Rock-floor

With the bedrock of the broad intermont plains possessed of the same geologic structures as the mountains, only thinly covered instead of deeply buried by detritus, and formed on a surface evenly planed off, the main interest centers around the agencies and conditions under which the planation was accomplished.

In the American region, with its fine patterned relief and the general plains surface greatly disturbed by recent faulting on a large scale, the even rock-floor worn out on the beveled edges of the rock strata long escaped merited attention. In southern Africa, where there is the same elevated plateau and the same dry climate, but where the region has not undergone notable deformation and dislocation for a long time, Passarge[10] has made the deduction that general planation may go on over a vast area without peneplanation; and that the leveling may be more perfect than is possible in the case of normal baseleveling. In the light of this suggestion, the existence under thin detrital covering of even rock-floors in the plains of the much disturbed region of the Great basin and the Mexican tableland acquires a new meaning.

Origin of the Rock-floor Surface

Peneplanation

At the time at which the beveled character of the rock-floors of some of the New Mexican bolsons was first recognized, in 1902, these even

[10] Zeitschrift der deutsche geologische Gesellschaft, lvi band, Protokol, 1904, p. 196.

surfaces were ascribed to peneplanation effects modified greatly on account of the great distance from the sea, the arid climate, and recent orogenic uprisings. The possible conditions were briefly outlined.[11] Among other statements, it was mentioned that the peculiar alternation of narrow mountain ranges and broad plains presents many features which are not easily understood until the country both to the eastward and to the westward is taken into account. In both directions from the central highland, or plateau, the basin character of the plains is soon lost. The different intermont plains become confluent and more continuous, and the mountain ranges become more distant from one another until finally they are widely isolated. Still beyond, the plain alone persists without noteworthy mountains. This condition continues on the one hand to the gulf of California and on the other to the gulf of Mexico.

A large portion of the plains part of the region is worn on the beveled edges of Cretacic and older strata. The Las Vegas plateau, the Llano Estacado, the bolsons of central New Mexico, and perhaps some of the broken plains of eastern Arizona seem to belong genetically together. Tight's[12] arguments to the contrary are clearly untenable, since in no uncertain terms he accounts for the physical features of the region on the basis of a humid climate.

That the general and dominant surface of eastern New Mexico may have been, in the main, originally essentially a peneplain appears to be indicated by old planation surfaces which are known to exist in the northeastern part of the territory. One of these old planation levels, the great Mesa de Maya, now only a relatively narrow belt, truncates the Raton range for a distance of over 100 miles. It lies 3,500 feet above the present plains surface. The range itself is all that is left of the immediate substructure of a once vast plain.

Three thousand feet below the level of the Mesa de Maya is a second great plain, the Ocate mesa, which covers thousands of square miles. Far beyond the borders of what now remains of this central body of the mesa are many large and small outliers of the same plain. Still lower, about 500 feet, is the general plains surface of the region, the Las Vegas plateau, which is on a level with, and at no distant date was probably continuous with, the Llano Estacado, the Estancia, the Jornada, and other large plains. Below the last-mentioned level the Canadian river, the Rio Pecos, and the Rio Grande have cut narrow valleys 1,500 to 2,000 feet and more.

[11] American Geologist, vol. xxxiv, 1904, p. 161.
[12] American Geologist, vol. xxxvi, 1905, pp. 271-284.

Under normal conditions of a humid climate the three general plains mentioned naturally would be regarded as representing as many different peneplanation levels, as indeed Hill has already urged; but their presence on the border line of the typically arid country suggests that all of these plains, with the possible exception of the Mesa de Maya, should be ascribed to desert-leveling instead of normal peneplanation. It is not unlikely that the Mesa de Maya is also a plain produced by desert-leveling; but assuming that it is not, and a true peneplain instead, general desert-leveling alone must be regarded as having removed from the plains a thickness of not less than 3,000 to 5,000 feet of rock materials. It is also very suggestive that this is also approximately the present heights of the desert ranges above the plains surface. This phase of the subject is capable of much further elaboration.

Eastern New Mexico is on the border of the humid and arid regions. Whatever may have been the later activities of the geologic processes under conditions of aridity, there seems to be good reason for believing that there was in this part of the Southwest something of the nature of a peneplain to start with, though its continuity may have been very much broken on account of profound faulting and orogenic deformation. As they now stand, it would hardly be proper to call either the general surface of the tableland or that of any of the intermont basins peneplains, in the strict meaning of that term.

PLANATION INDEPENDENT OF SEALEVEL

The fact that some of the bolsons of New Mexico were destructional plains instead of constructional plains, as had been generally regarded, was first personally impressed as early as 1902, after considerable detailed investigation in regard to the underground water supplies of the Estancia, Jornada, San Augustine, and other great plains of the region. A year later the first evidences bearing on this subject were published.[13] The article in which these facts were presented was of the nature of an advance paper taken from two more comprehensive reports on the "Geology and underground water supplies of the Estancia plains," and on the same general topic as relating to the Jornada del Muerto.[14] The first of these memoirs discussed in considerable detail the action of the wind as a leveling agent over broad areas and even as the chief agent in the excavation of large hollows and minor lake basins in the arid region.

During the following year opportunity presented itself to extend the observations over the greater parts of Arizona, Texas, Oklahoma, and old

[13] American Journal of Science (4), vol. xv, 1903, pp. 207-210.

[14] U. S. Geological Survey, Underground Water Supply and Irrigation Paper, no. 123, 1905.

Mexico. It was an easy matter to fancy that under the abnormal conditions of an arid climate and through means of eolian and sheetflood erosion local planation of the intermont areas might not only take place, but that the process might be general in character, notwithstanding the fact that the general plain thus formed was high above baselevel.

The idea became fixed by the proposal of a title meaning a surface of general planation of the earth, whether near baselevel in humid regions, far above baselevel in the dry lands, or below baselevel in the case of marine denudation. A new and distinct name for the surface of general planation in arid regions alone seemed inadvisable, especially since in southwestern United States such a plain merged on the one hand into a true peneplain and on the other into raised marine plains. It was thought for a while that the meaning of peneplain could be extended so as to cover the new field, and in this sense that title was actually used a number of times before abandonment. On account of these and some other "heresies," which have since been thoroughly substantiated, the full report on the Estancia plains was greatly delayed in publication, and finally rejected by the United States Geological Survey.

In the meanwhile appeared Passarge's important memoirs on the "Rumpffläche und Inselberge"[15] and "Die Inselgeberglandschaft im tropischen Afrika"[16] bearing on the same subject. Passarge, in the South African field, had greatly the advantage of the geologists who had visited the western American regions, in that he had to deal with a high desert region in the topographic stage of old age, and a region long undisturbed by mountain-making forces, instead of a country traversed by several large streams flowing through to the ocean, disturbed very recently and very profoundly and intricately cut up into huge blocks which have the appearance of earliest youth.

Passarge's conception is briefly and essentially this: That in the geographic development of the South African region there is finally a stage reached in which an elevated plain, under an arid climate, is reduced to a lower and evener surface chiefly through the blowing away of the fine materials, though aided occasionally by sheetflood, leaving a beveled rock-floor only thinly covered by ordinary soft deposits and having no relationship to the baselevel of erosion as commonly understood. To all intents, such a plain is a typical peneplain, wholly unrelated to the sea-level. Davis[17] well says that we may regard this generalization as secondary only to Powell's generalization concerning the general baselevel of erosion.

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[15] Zeitschrift der deutsche geologische Gesellschaft, lvi band, Protokol, 1904, pp. 193-209.

[16] Naturwiss. Wochenschr., new series, iii band, 1905, pp. 657-665.

[17] Journal of Geology, vol. xiii, 1905, p. 373.

In commenting on arid old age, Davis makes the statement that

"It is little wonder that an understanding of the possible development of rock-floored deserts of this kind, independent of baselevel, was not reached inductively in western America; for there has been so much disturbance in way of fractures and uplift in that region during Mesozoic, Tertiary, and Quaternary times that the attainment of old age has not been permitted; but that the problem was not solved deductively by the present generation of American physiographers before it was encountered and solved by others in Africa serves to show how insufficient still is the use of the deductive method among us."

There are apparently two very good reasons why American geologists did not reach a solution of the problem before it had been arrived at elsewhere. Deductive reasoning in geology is not always a very safe method without more or less of an inductive foundation. The great Colorado plateau, containing more than 200,000 square miles of area and situated more than a mile above sealevel, is mainly an even plain with a rock-floor but thinly veneered by waste; yet these facts never excited the notion of planation without the aid of water erosion. Moreover, Powell's grand deduction relating to this very same arid region was something very different from that proposed for the South African tableland. It gave us the conception of the baselevel of erosion which, as it now seems, was not entirely true of the arid region to which it was intended to apply, though it aptly fitted the humid lands of the earth far removed from the place of its birth. The philosopher Emerson somewhere says that when we go to Europe we see only what we take with us. With equal truth it may be stated that when we go on geological travels we are often too prone not to leave behind us some of our old notions.

In the second place, scientists have only briefly visited the arid regions; of these, few have ever lived there for any length of time and have become intimately acquainted with the peculiarities of the various geologic processes working under new conditions. As a result, most of these visitors have interpreted their observations more in accordance with the better known conditions of a humid climate than of the less familiar conditions of a dry climate.

SHEETFLOOD EROSION

McGee's graphic description[18] of sheetflood erosion has never received the recognition that it justly merits from writers on the arid regions. The remarkable phenomenon of the sheetflood is seldom observed to advantage except by dwellers within the dry belts of the earth. In these

[18] Bulletin of the Geological Society of America, vol. 8, 1897, pp. 87-112.

regions it is one of the most potent of degradational agencies, second only to erosion by the winds.

In humid lands recently elevated, where most of us have been accustomed to picture the evolution of general land forms, the most striking effect is the development of perfect stream systems with their accompanying valleys. In the arid regions the main effect of running water appears to be the very reverse. Instead of the attainment of ever more perfect drainage systems, the general tendency is toward complete obliteration of all evidences of distinct waterways. In place of sharply incised types of topography, there is the marked planation type of surface relief.

This plain-forming erosion, if it may be so called, has been so generally overlooked and of recent years the relief effects in the arid regions so generally explained on principles applicable only in a humid climate that it appears pertinent at this time again to direct special attention to some geologic factors peculiar to the dry countries. In the semiarid and arid districts of western America and of Mexico the inhabitants have long recognized this special erosive cause which tends to produce the plain effects. They have also given this phase of erosion a distinctive title. The provincial name is the floodsheet; and, as will be seen later, a very appropriate term it is.

The encounter with a floodsheet in a dry desert is something quite different from every other experience, and when once met with never to be forgotten. The sporadic but severe thunderstorms produce diametrically opposite effects in the mountains and on the plains. These "cloudbursts," as they are suggestively called by those dwelling in the arid regions, give rise in the hills, and often for a short distance from the foot of the ranges, to normal stream action of a very vigorous character. As the ephemeral torrents debouch from the canyons at the base of the mountains they quickly spread out into typical, though very local, floodsheets. McGee's account is of one of the latter and is as follows:

"During the 1894 expedition a moderate local rain occurred while the party were at a Papago rancheria near Rancho de Bosque, some 15 miles north of the international boundary at Nogales; the rainfall was perhaps one-fifth of an inch, sufficient to moisten the dry ground and saturate the clothing, despite the concurrent evaporation, and was probably greater in the adjacent foothills of the Santa Rita range. The road was sensibly level, having only the 20-foot-to-the-mile grade of the Santa Cruz valley; it ran across the much stronger slope from the range toward the river, and an arroyo embouched from low terraciform foothills not more than 200 or 300 yards up the slope. Thus the arroyo opened not on a perceptible fan, but on a sensibly uniform plain of sand and silt with occasional pebbles, sloping perhaps 150 feet to the mile. The shower passed in a few minutes and the sun reappeared, rapidly drying the ground to whiteness. Within half an hour a roar was heard in the foothills, rapidly

increasing in volume; the teamster was startled, and set out along the road up the valley at best speed, but before he had gone 100 yards the flood was about him. The water was thick with mud, slimy with foam, and loaded with twigs, dead leaflets, and other flotsam; it was seen up and down the road several hundred yards in either direction, or fully half a mile in all, covering the entire surface on both sides of the road, save a few islands protected by exceptionally large mesquite clumps at their upper ends. The torrent advanced at race-horse speed at first, but, slowing rapidly, died out in irregular lobes not more than a quarter of a mile below the road; yet, though so broad and tumultuous, it was nowhere more than about 18 inches, and generally only 8 to 12 inches, in depth, the diminution in depth in the direction of flow being less rapid than the diminution in velocity. The front of the flood was commonly a low lobate wall of water, 6 to 12 inches high, sloping backward where the flow was obstructed by shrubbery, but in the open curling over and breaking in a belt of foam like the surf on a beach; and it was evident that most of the water first touching the earth as the wave advanced was immediately absorbed and as quickly replaced by the oncoming torrent rushing over previously wetted ground. Within the flood, transverse waves arose constantly, forming breakers with such frequency as to churn the mud-laden torrent into mud-tinted foam; and even when breakers were not formed it was evident that the viscid mass rolled rather than slid down the diminishing slope, with diminishing vigor despite the constant renewal from the rear. Such were the conspicuous features of the sheetflood—a thick film of muddy slime rolling viscously over a gently sloping plain; and this film was a transformed stream still roaring through the rugged barranca only a few miles away."

The verity of the tremendous efficiency of the floodsheet has been amply attested by the experiences, for the past 20 years, of the railways traversing the Mexican tableland and the Great basin of western United States. Sheetflood effects have not attracted special attention mainly for the reason that when interfering with railway travel they are spoken of merely as "washouts." Of late years the various roads of the arid region of the West have expended very large amounts of money devising means of protection against the "floods." This is sought by attempting to direct the waters into artificial streamways. On the more elevated sides of the tracks are constructed long series of deep A-shaped ditches and high embankments. Where the bases of the contiguous triangles meet, trestles are built.

The railways, in other words, are making every endeavor to develop on the plains stream systems such as nature produces in the humid lands. Success is only partial. The plain-forming forces are stronger than man's weak efforts against them. The ever-shifting sands and loams are continually filling up the ditches and leveling off the embankments. When the sheetflood comes it rolls over the plains and buries the tracks or floats them off. It works in the same way as it has for centuries.

Locating engineers of railroads have yet to learn how to properly make surveys across the arid country.

In August, 1906, one of the trains carrying some of the members of the International Geological Congress to the city of Mexico passed, in the state of Chihuahua, through five floodsheets in a single day. One of them, on a plain with a noticeable grade, appeared, as far as eye could reach, like a lake with shrubbery everywhere growing out of it. When closer inspection was made it was soon found that the waters were in rapid motion down the slope, which happened to be toward the railway track. Part of the floodsheet reached the track before the train succeeded in getting beyond its effects and buried the roadbed in mud. The train following was delayed hours, and it was afterward learned that the mud covered the tracks in places to depths of more than 2 feet. The roadbed for a distance of more than 3 miles was completely lost to view.

McGee, I think, greatly overestimates the actual extent of sheetflood action as a destructive agency of erosion. It is of great significance that he recognizes throughout the Sonoran district which he describes, and far beyond its borders, that the intermont plains all have rock-floors, in most places only very thinly veneered with sands and silts. He ascribes this condition entirely to sheetflood work. Sheetflood action is probably secondary to eolian action in these regions. Sheetflood effects are very local and of sporadic nature; wind action is universal and constant. A floodsheet may visit a given locality only once a year; the wind blows over the plains all the time.

EOLIAN EROSION IN ARID REGIONS

In the arid regions the wind is probably not only the most potent of the gradative agencies, but its efficiency is greater than all other geologic processes combined. The cooperation of sheetflood activities in making the plains is important; without extensive wash the present smoothness of the plains would be impossible.

The main activity of the wind is manifestly degradational in character. The constructional effects are local and relatively unimportant. It is thought that in the arid regions of western America the wind has been a general leveling agent the importance of which has been little suspected.

Throughout the dry regions "dust storms" are violent and frequent. During their progress their effects in producing personal discomforts have commonly blinded all, even trained scientists, to their real geologic significance. While these dust storms last, and even for several days afterward, the air is so filled with fine soil that it is often impossible to

see objects more than a comparatively short distance away. The sun is frequently obscured as by a heavy raincloud. The dust floats upward thousands of feet above the surface of the ground and remains suspended for days at a time or is blown away to distant regions. The amounts of fine materials thus carried away must be enormous.

The tremendous effects of the dust storm or sand storm on the Sahara and Arabian deserts have been known since earliest historic times; but they have been looked upon as merely freaks of idle shifting sands rather than of powerful and persistent geologic agents. Some of the geologic effects of the wind as a denuding power have been recently ably discussed by Walther,[19] whose observations were made chiefly on the northern African deserts. Similar wind effects on the bare sand bars of the Missouri river reproduce on a small scale and under a humid climate the conditions of great desert regions.[20]

Dust alone is not only transported by the winds, but sands and even pebbles are swept along with much force. On the bare rock surfaces these act as a sand blast, polishing the harder ledges until they appear as if they had been actually fused. Under the influences of streaming sands, all outcrops are rapidly worn away at a rate many times faster than by running waters. During a single "storm" large areas of bare rock may be uncovered, exposed to the triturating action of the moving sands, and become again covered by a mantle of loam and sand. Shallow basins, from a few hundred yards to several miles across, may be hollowed out of the plains surface that may afterward be filled with storm waters, producing lakes. Gilbert[21] has ascribed some such origin to certain ponds in western Kansas. In the desert regions the eolian genesis of minor lake basins appears to be more prevalent than is commonly supposed.

Among the larger effects of eolian action is general planation, a process which in dry lands corresponds in its ultimate results to baseleveling in humid regions. It now appears that to this agency, assisted by the sheet-flood, should be ascribed the chief cause of the even rock-floors of the basin plains of the arid country. By it the surfaces which are worn out on the beveled edges of the rock strata are formed in the same way as the peneplain is evened off by means of water action. The process is probably more rapid on the whole than that giving rise to peneplanation.

[19] Abhandlungen Königlichen Sächische Gesellschaft der Wissenschaften, xvi band. 1901.

[20] American Journal of Science (4), vol. vi, 1898, pp. 299-304; also Bulletin de la société Belge de géologie, du paleontologie et d'hydrologie, tome xii, 1901, pp. 14-21.

[21] Journal of Geology, vol. iii, 1895, pp. 47-49.

Much of the supposed general leveling effects ascribed to sheetflood erosion should be probably attributed to eolian activity.

PLAYA DEPOSITS

In the Basin Range region it has been customary to regard the intermont plains on the one side as deeply covered by waste which gradually becomes thinner until finally the bare surface of the tilted block emerges and passes into the mountain elevation (figure 6). Most of those persons who have had to deal with the basin ranges of western America have thus interpreted the underground structure of this region. It now seems that this idea is due to a purely deductive conclusion based on wholly erroneous premises.

Later observations recognize three distinct belts of relief: (1) The dissected highlands, composed usually of bare rock-masses; (2) the graded piedmont slopes, made up of more or less angular and coarse rock-waste, and (3) the aggraded central plain, composed of fine clays

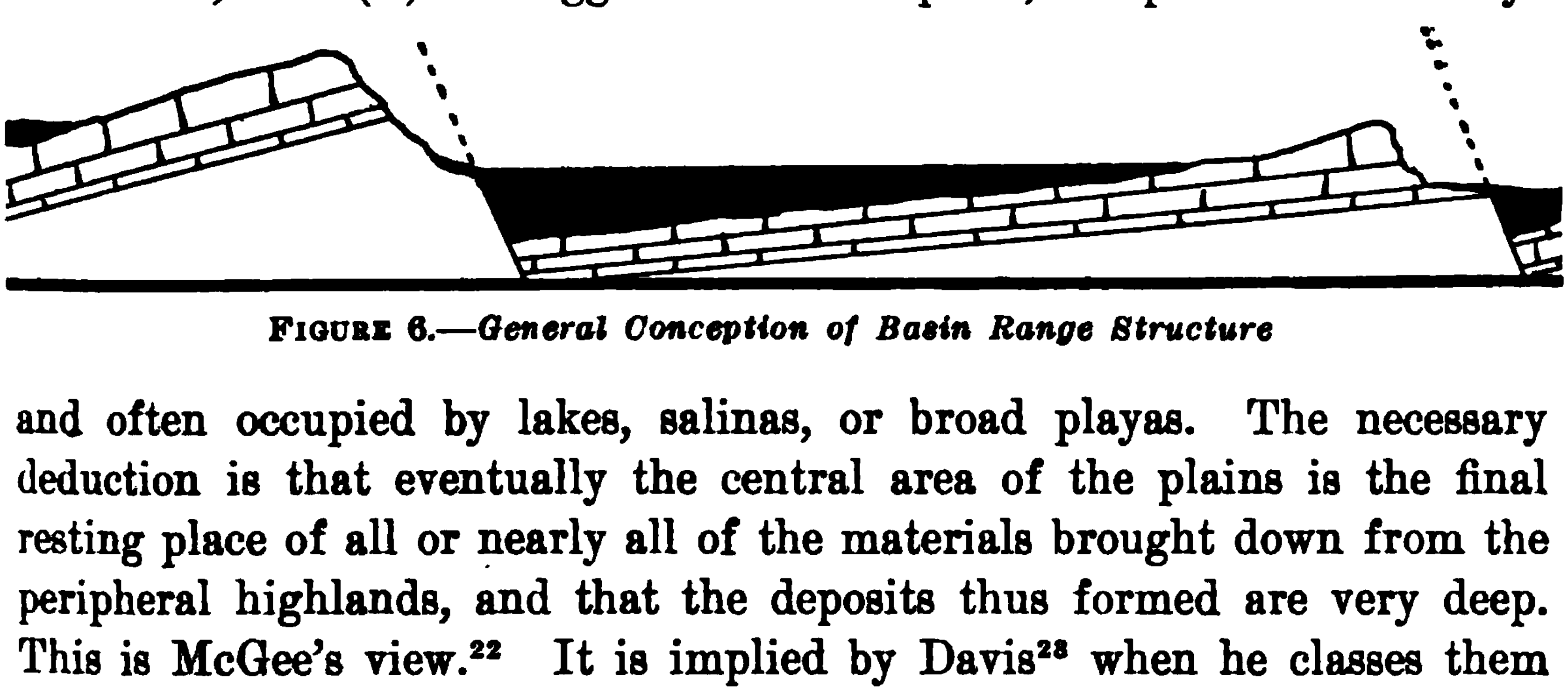

FIGURE 6.—*General Conception of Basin Range Structure*

and often occupied by lakes, salinas, or broad playas. The necessary deduction is that eventually the central area of the plains is the final resting place of all or nearly all of the materials brought down from the peripheral highlands, and that the deposits thus formed are very deep. This is McGee's view.[22] It is implied by Davis[23] when he classes them as aggraded areas, at least during the earlier stages of the arid cycle. It seems to be also the conclusion of every casual observer. It suggests itself as the only possible alternative, especially when the valley plains have no outlets, but are truly inclosed basins.

There are many transitions, among these intermont basin plains, from those holding extensive and permanent lakes to those which are perfectly drained. The stage known as the playa is one in which there is a broad expanse of barren silt; "dry lakes" they are usually aptly called. Waters are only brought down once or twice a year from the surrounding mountains, and cover the mud-flat to depths of a few inches or a foot or two. Such lakes are very short-lived, lasting only a few weeks at most. Nine or ten months out of the year the areas occupied by them are dry flats.

[22] Bulletin of the Geological Society of America, vol. 8, 1897, pp. 87-112.
[23] Journal of Geology, vol. xiii, 1905, p. 387.

Playas and similar mud-flats of the arid plains must be regarded as areas of great degradation as well as areas of aggradation. It is doubtful whether in the great majority of cases the former lags little or any behind the latter. When the waters are finally all evaporated the playas are veritable "mud-flats." This bottom mud as it dries curls up into leaves a millimeter or two in thickness and several centimeters across. The first strong wind that comes along blows these leaves away like the fallen foliage of the trees after the first blast of winter. Much of this material is carried bodily away, miles out of the playa area, or gathers in huge windrows about its margins. A large part is ground to dust in the moving about and is then carried off like other dusts of the plains. With every shower that falls on the playa, there is the same mud layer again formed and further exportation of the material.

When old playas have been cut through by recent torrential or stream corrasion the soft deposits appear, in a number of observed instances at least, to have no very great thickness. In the Meadow valley, in southeastern Nevada, for example, 100 feet beneath the surface of the old playa, the hard rock-floor of the plains is in evidence—ancient limestones, sandstones, and shales highly inclined and horizontally and evenly beveled. In the Amargosa valley of southeastern California similar phenomena are presented. In the remnants of the old bolson surfaces along the Rio Grande there is often displayed the ancient rock-floor surface high above the present level of the existing channel.

Many salinas exhibit like conditions. In the great Hueco bolson, in central New Mexico, are shallow alkaline lakes which are dry for the greater part of the year. As the waters dry up, a thin sheet of various salts, chiefly gypsum, is left on the bottom. This soon curls up into thin leaves, which when blown together are quickly broken up into gypsum sands and salt sands. The winds carry the white sand out on the plain, where it gathers into immense dunes, 60 to 100 feet in height, miles wide and a score of miles in length (see plate 5).

The central flats of the intermont plains of the arid districts are, then, not always areas of constant aggradation, as has been commonly inferred, but are areas of most rapid degradation as well. In some of the central flats a rock-floor is known to exist at shallow depths. In the large majority of them nothing is as yet definitely known regarding the character or the depth of the substructural surface. Whenever any of the last mentioned class have been examined carefully as to the depth of their rock-floors the mantle of detritus has been found to be of no great thickness. In a few cases great thicknesses of surface materials no doubt exist, but most of those which have been so reported do not appear to be thus deeply

GYPSUM SAND DUNES

In the Hueco bolson, New Mexico, 60 to 100 feet high

buried. With few exceptions, such reported observations must be submitted to further scrutiny before they can be fully relied upon. The recent assertions of Tight[24] and of Lee[25] are categorical in the extreme, and have to be taken, in the light of recently observed facts, with extreme caution. In the case of the Albuquerque deep well being 700 feet in soft mesa deposits, it is significant that the main water supply of this well comes from levels less than one-half of this distance from the surface, and that the strata beneath this level appear strangely like the uppermost Cretacic sands of the local geologic section. It would not be surprising to find also an extensive section of the Eocene Puerco deposits at a level only a short distance beneath the river bed.

On the whole, the ascribed thicknesses of aggraded materials in the central portions of the basins under consideration is, as yet, largely a result of inference to fit an hypothesis rather than a matter of careful observation on actual conditions. There are probably, in different parts of the arid country, all gradations, from the basins with deep aggraded substructure to those in which there is merely a veneer or even bare rock. The significant fact remains that in the majority of cases in which there have been careful observations made there is a rock-floor at very shallow depths. Such facts are in perfect accord with the evolution of the general relief features under conditions of an arid climate, where wind, and not water, is the dominant factor in giving expression to the earth's surface. Facts of this class are also in harmony with our ideas regarding complete leveling of high-lying surfaces without baseleveling.

ARID PLAINS OF OTHER REGIONS

The idea of the planing off of a high-lying land-mass without being first reduced to baselevel was developed mainly by Passarge[25] for the vast dry plains of South Africa. To this region reference has been already made in some detail.

Bornhardt's description[26] of the elevated plains of German East Africa indicates that the main epoch of planation was one of aridity. In northern Africa the Libian and Nubian deserts present in many places a firm rock-floor at slight depths, the full significance of which has never been appreciated until Passarge emphasized the fact elsewhere. From the accounts of travelers the interior of the Sahara desert have characteristics not unlike those of some of the plains districts of western America. On

[24] American Geologist, vol. xxxvi, 1905, p. 279.
[25] U. S. Geological Survey, Water Supply and Irrigation Paper, no. 188, p. 190.
[26] Zur Oberflächengestallung u. Geologie Deutsch-Ostafrikas, Berlin, 1900.

this point the observations of Walther[27] in northern Africa are of great interest.

In the central Asian desert belts the planed surfaces of such flat-topped mountain ranges as the Bural-bas-tau and other similar ridges in the great Tian Shan system were formerly[28] considered as remnants of an old peneplain uplifted to heights of 12,000 feet and over. Regarding them the question has been more recently raised by Davis[29] that they might possibly be partly, if not wholly, due to leveling without baseleveling, under conditions of arid climate; but the existence of a peneplain, draining to the sea, in the northern part of Asia would, according to this author, seem to militate against this suggestion. Farther to the westward, in the Caspian basin and also even in the southern provinces of European Russia, the beveled rock-floor of the steppes, even though lying so near or even below sealevel, may be largely the result of desert-leveling rather than of base-leveling. Bearing directly on this point, Penck[30] has suggested that so long as the waters of the sea do not have free access to the area a desert surface may be readily excavated considerably below mean tidelevel.

The great desert plains of Australia are in need of careful scrutiny with this idea constantly in mind of general leveling under conditions of aridity instead of under conditions of normal peneplanation.

PLANORASION

In the normal cycle of evolution of land forms under conditions of a humid climate the dominant process is stream corrasion. The ultimate product of a general plain is the least important stage. The process is known as peneplanation. In the geographic cycle under climatic conditions of aridity stream action is of small consequence. A plains surface is persistently maintained throughout the cycle, or at least from a time very soon after its inauguration. The plains feature is, as fully attested by the observations of Passarge, smoother than is possible with the peneplain. The ultimate product is a general plain but slightly different from that existing through the whole period during which the plains-forming process has been in action. It is essentially planorasion.

Geographic Cycle in an Arid Climate

The foregoing observations are intended as a contribution to our knowledge of the substructure of the plains in the dry regions of the West, and

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[27] Das Gesetz der Wüstenbildung, Berlin, 1900.
[28] Appalachia, vol. x, 1904, pp. 277-284.
[29] Journal of Geology, vol. xiii, 1905, p. 405.
[30] American Journal of Science (4), vol. xix, 1905, pp. 165-174.

particularly of the Great basin and of the Mexican tableland. The facts recorded are given as concrete proofs of general leveling of elevated areas of great extent without baseleveling and of the possibility of an arid cycle in a given district and under special conditions.

As noted by Passarge in the South African plateau, the essential characteristics developed during far advanced stages of the arid cycle appear to be as clearly displayed in the American dry country. He makes little reference to the earlier stages which are especially characterized by Davis, who considers the arid cycle in its entirety. For the region under consideration the salient features are (1) true plains of vast extent, above which rise abruptly the isolated mountains; (2) general absence of foothills; (3) highlands composed of hard rocks and lowlands of soft rocks; (4) rock-floor a plain itself on the beveled edges of the strata; (5) rocks without surface decomposition; (6) mantle of loose detritus relatively thin; (7) rock-waste transported; (8) waste debris merely rendering the plain smoother.

In his generalities, in formulating the scheme of the arid cycle Davis[31] goes far beyond Passarge.

"It thus seems [says the American author in conclusion] to be as well supported by appropriate facts as is the scheme of the normal cycle; it is, indeed, in one respect even better supported, for while the African plains are examples of old desert plains now growing still older, it is difficult to point out any large peneplain that still stands close to the baselevel with respect to which it was worn down."

The "Inselberglandschaft" of South Africa is described by both Bornhardt and Passarge as composed of residual mountains rising island-like out of the great plain. In western America the nearest counterpart is found in southwestern Arizona. Here the mountain ranges are composed of lofty masses of very resistant rocks, chiefly andesites and rhyolites in extensive bedded sections after the manner of clastic formations. The layers are not noticeably tilted. The almost vertical walls and precipitous slopes on either side of a range display the horizontally lying edges of the lava beds frequently for thousands of feet in vertical section. The cross-section of the Plomas mountains, as an illustration, represents this structure as given below (figure 7). These mountains are, perhaps, true residuals.

In the case of the tilted block mountains, which are most characteristic of the Mexican tableland, the ranges can hardly be considered as wholly residual. Most of them have had the soft rocks, which are now only ex-

[31] Journal of Geology, vol. xiii, 1905, pp. 381-407.

posed at the foots of the longer slopes, eroded from their summits. These blocks are not simple residual elevations, since they have been partly reared through recent and profound faulting. How much of such mountains should be ascribed to strictly residual effects and how much to elevation above the adjoining plains would have to be determined in each particular instance. Ordinary desert-leveling has been greatly complicated by extensive extravasation as well as by profound orogenic movements. The specific effects of epeirogenic movement have never been considered.

The observation is made by Davis[32] that "no special conditions need be postulated as to the initiation of an arid cycle. The passive earth's crust may be (relatively) uplifted and offered to the sculpturing agencies with any structure, any form, any altitude, in dry as well as in moist regions." While this statement is eminently true under conditions of a wet climate, a little reflection must make it clear that it is not necessarily so with respect to a dry country, where the dominent erosive agency is entirely distinct. In an arid climate, according to the writer just quoted, the typical initial condition of the earth's surface is that of a more or less rugged mountainous region.[33] In a moist climate, in which there is a succession of completed cycles, the most typical initial condition of surface relief is that of a peneplain. Instead of postulating similar topographic types, the beginnings of the normal and the special cycles are considered as taking place under the most antithetical of relief effects possible. This surely is not necessarily so.

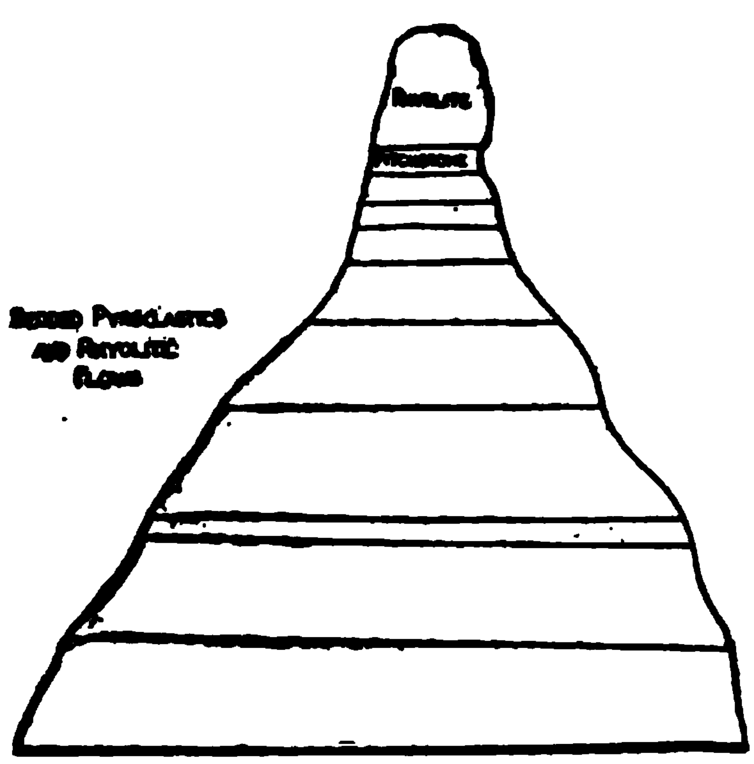

FIGURE 7.—*Profile of Crest of Plomas Range, Arizona*

Vertical distance about 1,000 feet

For the initiation of an arid cycle the selection of an antithetical type of relief instead of a normal type, as would naturally be expected, appears to be due largely to deductions resting upon present conditions obtaining in the desert regions of western United States and central Asia. So far as this country is concerned, there seems to be as yet very little specific exemplification brought out in support of the contention. In reality, what is actually postulated in the Davis scheme of an arid

[32] Journal of Geology, vol. xiii, 1905, p. 382.
[33] Ibid., p. 380.

climate are highly specialized initial conditions in place of generalized, typical, or "no special" conditions.

Under ordinary conditions of climatic aridity the initial relief may be regarded as being either one of two extreme types. One is the rugged mountainous type of topography, and the other is the general plains type, as in the normal cycle—the peneplain, if you please. Only the first mentioned type could serve for the foundation of the distinctly marked scheme of an arid cycle, as recently so astutely developed by Davis; the second would result in a scheme of general desert-leveling, with no distinct stages, as formulated by Passarge. As will be noted later on, the occurrence of instances of the first named scheme, corresponding in all of its phases to those of the normal cycle, must be very rare indeed. The prevailing mode of leveling and lowering of an arid country must be very largely after the fashion described for the South African region. The latter region would thus represent the general course of desert-leveling, rather than only the senile stage.

With an upraised peneplain, the degradational processes may start to reduce the country toward ultimate baselevel just the same under conditions of an arid climate as under conditions of a moist one. When the wind is the chief erosive agency the resulting topographic effects are not so very unlike the general relief effects produced by the streams. The belts of hard rock are brought into somewhat stronger contrast, perhaps, than in moist climates. The geologic structures are more sharply accentuated. The rock-floor is cleaner swept. The belts of weak rocks are faster removed. At all times the plain is more strikingly the dominant relief feature. If after the main epeirogenic movement orogenic activity remains quiescent, the general plain continues indefinitely to persist without marked change of expression, as is clearly the case of the South African tableland, where there would be no distinct stages marking the evolution of the arid cycle. Epeirogenic movement followed by frequent and widespread orogenic disturbances, and also by vigorous volcanic activities, as in western United States, would soon obliterate most evidences of a former peneplain, if such ever existed over the region. There are strong reasons for believing that such a peneplain actually did exist there at the beginning of the period of aridity.

When critically examined the scheme of an arid cycle, distinctly staged and beginning with a rugged mountainous relief, is found to be in reality the evolution of the normal wet cycle with somewhat less water. If the periods of infancy, youth, and maturity could exist, they must be so brief, compared with the duration of the characteristics of old age, that they become stages altogether negligible, even when starting with a moun-

tainous relief. Beginning with a plains relief, they surely would be entirely out of the question. Considering the present desert mountains of western United States as very recent features and as initiated subsequently to the introduction of the arid climate, as now appears altogether likely, the earlier stages of the dry cycle must have been very different from those depicted.

Professor Davis distinctly makes water action the most efficient erosive agent of the arid region, ascribing a very secondary rôle to the wind. In a country with only 10 inches and less of annual rainfall, nineteen-twentieths of which sinks into the ground as soon as it touches the surface, and does not appear as stream water at all, it is exceedingly difficult to understand how water can have the greater erosive force. For an arid region, southwestern United States is anomalous, because it contains several large rivers flowing through to the sea. It is to be remembered that these streams merely traverse the arid country, and are not in fact in any way an essential part of it. These rivers are of large size; their headwaters are in the moist regions; they have very high gradients; they all carry vast volumes of silt; they receive no lateral augmentations to their waters in passing through the dry country, and carry to the ocean from the arid region about as much rock-waste as do the Arkansas, Platte, and Missouri rivers from their basins. It is perhaps for this reason, more than any other, that the rock-floor of the arid plains is so well displayed at small depths. Where the direct influence of the through flowing streams is not so apparent, as in Nevada, the transported sands and soils drift about more and accumulate into vast sand dunes, just as they do on the streamless Lybian and Nubian deserts.

The importance of Passarge's great generalization lies in the suggestion that it is possible under conditions of an arid climate for the general planation of vast areas to go on without regard to the sealevel. For a long time this author[34] found great difficulty in accounting for the great plains surfaces by wind action alone, for the reason, as he explains, that the wind has no baselevel of erosion and must continue the work of excavation and removal wherever the rock-floor is not resistant. Recently Penck[35] has suggested that so long as the sea is held out a desert surface might be worn down to a level below that of the tide. There seems to be, however, a limit even to this desert-leveling and eolian excavation. The ground-water level in a structurally inclosed basin must finally limit the effects of wind action by keeping the surface moist, either giving rise to salinas or forming a basin into which sporadic storm

[34] Zeitschrift d. deutchen geol. Gesell., lvi Band, 1904, Protokol, p. 108.
[35] American Journal of Science (4), vol. xix, 1905, p. 165.

waters find a long resting place.[36] This would seem to be the case of the Death and Imperial valleys of California, the basin of lake Eyre in Australia, the Aral and other basins of western Asia, and many great hollows in the Sahara desert. While theoretically there might not be a downward limit to wind erosion in a dry climate, as Penck notes, so long as the sea is held back, there appears to be in reality a final level beyond which eolian excavation does not go. This level is no farther below sea-level than the final position of the peneplain is above it in a normal cycle. Ground-water level appears to be an important limiting factor to the erosional effects produced by eolian action, at least temporarily and locally. Of this class are many of the basins of the Mexican tableland, notably the Estancia, Hueco, Casa Grande, and Mapimi bolsons. While ground-water level, of course, lowers with the general lowering of the land surface, the rate is not always quite so fast. A level is finally reached in some localities where the upper surface of phreatic waters reaches sky.

Our science owes much—very much more than can be stated at this time—to Passarge and Davis for their broad deductions regarding the nature of arid erosion and desert phenomena, which have until within the last lenstrum remained inexplicable.

Recapitulation

It appears from the foregoing statements that in the arid regions of western America—

(1) There exists a vast general plains-surface, above which rise abruptly the numerous lofty mountain ranges;

(2) The plains occupy the areas of weak rocks and the mountains the areas of resistant rocks, the geographic extent of which areas has been largely determined, in order of their importance, by local extravasation, dislocation, and deformation;

(3) Bolsons, at least the original types selected, are destructive plains rather than constructive valleys, as they have been defined;

(4) There exists nearly everywhere in the arid region, at no very great depth, a distinct rock-floor; this generalization is not inconsistent with the idea of the presence of deep waste in the earlier stages of the arid cycle;

(5) The rock-floor is itself a plain, formed on the beveled edges of the rocks;

(6) The detrital mantle of the intermont plains is, on the whole, rela-

[36] American Journal of Science (4), vol. xvi, 1903, p. 377.

tively thin instead of being of great thickness, as heretofore generally regarded;

(7) The central playas, which many of the intermont plains contain, are areas of great eolian degradation as well as of sheetflood aggradation;

(8) The main denuding and leveling agent is eolian in character;

(9) Water action has a very subordinate influence;

(10) Sheetflood erosion has a general importance in plain-forming that has long been overlooked; Development of a general pl[illegible] under arid conditions

(11) What valley corrasion is in the humid region, planorasion is in the dry regions;

(12) Under conditions of an arid climate, a general plain of great extent may be formed without reference to baseleveling;

(13) The main significance of a definite rock-floor to the desert plains is the verity of eolian erosion as the chief factor in the geographic development of an arid country.

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OCCURRENCE OF PROUSTITE AND ARGENTITE AT THE CALIFORNIA MINE, NEAR MONTEZUMA, COLORADO[1]

BY FRANK R. VAN HORN

(*Read before the Society December 30, 1907*)

CONTENTS

INTRODUCTION AND BRIEF DESCRIPTION OF MINE

During the fall of 1902 the officers of the Mine Developing Company of Cleveland presented the geological department of Case School of Applied Science with several vein sections and specimens of high grade silver ore from their California mine in Colorado. The writer has obtained most of his information concerning the mine from the officials of the company, whom he wishes to thank for both information and specimens.

The California mine, formerly known as the Bell property, is situated on Glacier mountain, about 3 miles from Montezuma, Summit county, Colorado. The ore occurs in a fissure vein having a dip of approximately 30 degrees to the northwest and a strike which varies from 30 to 50 degrees northeast and southwest. The country rock is a coarsely foliated granitic gneiss in which the biotite has altered to chlorite minerals near the vein; this alteration was probably due to normal weathering, and not to the action of the solutions which deposited the vein matter, as no cases of impregnation of ore minerals were noticed outside the vein wall in any

[1] Manuscript received by the Secretary of the Society December 30, 1907.

of the specimens under observation. In hand specimens the foliation of the gneiss is not always distinct, and the rock is locally known as granite. The vein varies in width, and frequently has a massive granular appearance, but sometimes possesses a banded structure due to symmetrical deposition of minerals; at other times a more or less brecciated appearance is noticeable, which was probably caused by movements of the vein walls on each other. The surrounding region is more or less faulted, and at one place in the mine, the main ore body has been dislocated and shows slickenside surfaces. The vein is separated from the gneiss by a wide clay selvage, or gouge, which causes more or less trouble by caving in.

Principal Ore of Mine and Assays of Same

The ore occurs in streaks in the vein, varying from 1 to 21 inches in width, and consists principally of argentiferous galena, although in places large amounts of sphalerite are mixed irregularly through it. As a rule, both galena and sphalerite are coarsely granular, the crystals of each varying in size up to 3 inches in diameter. Some assays were made, which show an interesting variation of silver and lead values in the different pay streaks of the vein as follows:

No. 1, 1 inch wide; silver, 86.5 ounces per ton; lead, 34 per cent.
No. 2, 2-3 inches wide; silver, 11.0 ounces per ton; lead, 33 per cent.
No. 3, 4 inches wide; silver, 17.0 ounces per ton; lead, 65 per cent.
No. 4, 4-5 inches wide; silver, 34.0 ounces per ton; lead, 64.5 per cent.
No. 5, 5 inches wide; silver, 19.0 ounces per ton; lead, 47 per cent.
No. 6, 14 inches wide; silver, 25.8 ounces per ton; lead, 80 per cent.

An inspection of the above assays shows that the streak which ran highest in silver values contained the lowest percentage of lead, and that the one with highest lead contents gave results low in silver. This shows that the amount of silver does not depend on the quantity of galena present. It might be suggested that the variations in silver values could be explained by the presence of proustite and argentite mixed with the galena and sphalerite. However, the above assays were made long before the discovery of the rich proustite-argentite ore which will be described later in this article, and, as far as the writer can learn, those minerals were never found in the mine before the present discovery. Therefore it would seem that the variations in silver were probably caused by argentiferous galena in which the silver contents varied considerably. Possibly there is not sufficient evidence to warrant the speculation, but it occurs to the author that the different streaks might possibly have been deposited from

different solutions. This explanation would account for the variation of silver and lead values shown in the assays.

Occurrence of the Proustite

In September, 1902, the largest pay streak of the vein widened to about 21 inches and assumed a distinctly banded structure, with galena and sphalerite irregularly mixed on each side; these were followed by siderite, also symmetrical, while in the center was a streak of massive proustite with finely intermingled quartz which was more or less drusy. This streak was usually about 2 inches in width, but in one instance amounted to 14 inches. The proustite possesses all its usual mineralogical characteristics, which require no further description. For a very short distance the central portion consisted of argentite and finely disseminated quartz or a mixture of the two with proustite. When the latter predominated along the vein, no argentite could be observed, whereas in many of the argentite specimens proustite was detected. The proustite ore was followed along the strike for a distance of 30 feet with an upward stope of 20 feet, at which point it disappeared. By means of a winze and crosscut, it was also followed downward 15 feet until mining operations were suspended in the winter. The average specific gravity of four specimens of the proustite-quartz ore was found to be 4.17 as compared with 5.60 for the pure proustite. Several quantitative blowpipe determinations showed an average of about 20 per cent silver or about 6,000 ounces to the ton for the specimens examined. This would indicate about 33 per cent of the ruby silver, while the average specific gravity obtained would indicate a little over 50 per cent proustite.

Mr J. C. Sharp made two quantitative analyses of carefully selected proustite, the average of which gave as follows:

	Found	Theoretical (Ag_3AsS_3)
Ag	67.60	65.5
As	13.85	15.1
Sb	.93	....
S	17.40	19.4
	99.78	100.0

The analysis shows that a small amount of the pyrargyrite molecule (Ag_3SbS_3) is present, as is the case with certain proustites from Chile and Germany. That the percentage of silver found is apparently too high, while the sulphur comes lower than the theoretical amount, is probably due to an imperfect analysis, but might have been caused by the

presence of native silver, although none was perceptible. Silver, however, was observed on the argentite described later. Professor A. W. Smith very kindly recalculated the analysis on the assumption that the antimony replaces arsenic. It was found that .93 per cent of antimony is equivalent to .58 per cent of arsenic, which makes the total of the analysis come still lower than the original, as follows:

Ag	67.60
As	14.43
S	17.40
	99.43

This calculation shows the arsenic to be .67 per cent low when compared with the theoretical amount, which is 15.1 per cent.

Using the arsenic of the above as a basis of calculation of proportions in the theoretical formula of proustite, Ag_3AsS_3, we find the following requirements:

	Required	Found	
Ag	62.62	67.60	4.98 excess.
As	14.43	14.43	
S	18.54	17.40	1.14 deficit.
	95.59	99.43	

The above calculation proves at least an error in the determination of sulphur, but also indicates that native silver may probably be present. According to the last results, the original substance analyzed may have had the following composition:

Proustite	95.59
Silver	4.98
	100.57

Occurrence of the Argentite

The argentite specimens, which vary from 2 to 3 inches in width, are generally massive and finely granular, but in some cases are quite coarsely granular. As was indicated in the description of the proustite occurrence, the argentite seems to replace the proustite in the central portion of the vein for a short distance. In two instances a reduction of the argentite to native silver in wire-like forms was observed. The coarsely granular material is evidently purer, but all specimens are completely sectile and malleable. That the mineral, however, is not pure is shown by the

fact that the average specific gravity of three samples was found to be 6.55 as compared with 7.28 for the pure argentite. Quartz is sometimes observable with the naked eye, and, as was mentioned above, proustite can often, though not always, be seen on the argentite specimens.

The average of two analyses of the argentite made by Mr R. B. Dennis is as follows:

Ag	83.57
S	12.66
Insoluble	3.62
	99.85

The analysis was recalculated with the insoluble matter left out, with the following results:

	Found	Theoretical
Ag	86.71	87.1
S	13.13	12.9
	99.84	100.0

The lower specific gravity (6.55) mentioned above conforms in general to the amount of insoluble matter in the original analysis and probably is due to the finely disseminated quartz.

Paragenesis of the Ores

Owing to the limited number of specimens which could be studied and the fact that the author has never visited the mine, it does not seem warranted to enter into a very extended discussion concerning the order of deposition of the various ores mentioned above. One vein section was observed which was about 14 inches wide and consisted entirely of an irregular mixture of coarsely granular galena and sphalerite. No other conclusion seems justified but that both minerals were deposited at the same time. Another section described above under the occurrence of proustite shows the symmetrically banded or ribboned structure called crustification by Posephny, which is considered as showing simple fissure filling. This specimen contained the same irregular mixture of galena and sphalerite on each side, followed by siderite, likewise symmetrical, while the center was filled with the drusy mixture of proustite and quartz. In still another section the same order is followed, except that argentite is substituted for proustite. According to this arrangement, the galena and sphalerite were deposited at the same time, followed by siderite, while the

last to be precipitated was the mixture of proustite and quartz or argentite and quartz. From the solubility of these various minerals it would seem probable that here, also, the ores were deposited from different solutions at different times, which was the conclusion drawn from the assays given above, all of which were made before the discovery of the rich silver minerals.

It seems plausible that there were two silver solutions, one first furnishing the argentiferous galena, while the later one deposited the proustite and argentite along with quartz. Although apparently of later origin, in no case were the silver minerals found penetrating through the siderite into the galena and sphalerite, which would indicate that there was no later fracturing or opening of the fissure while the filling of the same was taking place. The walls of the vein seem everywhere sharply defined, and no replacement of the country rock was noticed. It might be mentioned that the officials of the company working the mine have a decided opinion that more sphalerite has been encountered in the lower levels than above. Likewise no proustite and argentite were ever found in the older workings above. This indicates an enrichment of the vein below, which might be due to solution of upper deposits and precipitation of the same in the lower levels. There was no evidence observed which would warrant this assumption, however, and it seems more probable that the change of ores has been caused by other conditions, such, possibly, as variation in pressure, temperature, or chemical composition.

Conclusion

The chief incentive in writing this article was to record the new occurrence of proustite and argentite in this particular locality. The writer has also never seen or heard of such massive specimens in such large amounts from any other region. On account of these facts, this paper has been deemed worthy of presentation before this Society, and specimens of both minerals in vein sections are submitted for inspection, hoping that they may prove of interest.

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PROBABLE AGE OF THE MEGUMA (GOLD-BEARING) SERIES OF NOVA SCOTIA[1]

BY J. EDMUND WOODMAN

(Read before the Society December 28, 1906, and presented by title December 30, 1907)

CONTENTS

INTRODUCTION

The gold-bearing rocks of the mainland of Nova Scotia have been under examination for more than fourscore years. Their structure and the methods of occurrence of their veins and the included metal have been studied in considerable detail; but from the earliest speculation of Gesner to the latest papers, references to the age of the series have been either vague or dogmatic without the requisite evidence to substantiate the statement. In recent years authors have for the most part been satis-

[1] Manuscript received by the Secretary of the Society February 1, 1908.

fied with following the lead of earlier writers in calling the series Cambrian. The present paper aims to assemble whatever evidence is available bearing upon the age problem; and while the results are far from satisfactory and lack definiteness, they at least may indicate the extent of the existing uncertainty and possible lines of inquiry designed to eliminate that uncertainty.

Difficulties which lie in the way of establishing the age of the Meguma series appear early to the student; for he has to deal with a group of rocks nearly 30,000 feet in thickness, apparently conformable throughout, remarkably monotonous in texture, practically barren, and exhibiting neither a base beneath which is exposed an older series nor a summit above which lie any fossiliferous formations of such age as will aid much in establishing that of the gold-bearing rocks. In all the 30,000 feet there has been discovered but one horizon which can be traced far—the contact between the lower quartzitic Goldenville formation and the upper slates, the Halifax formation.

History of Opinions

Without going into details, the fluctuations of opinion regarding the age of the Meguma series are as follows: Gesner (1843) called it Cambrian, without assigning reasons. Dawson (1850) regarded it as Lower Silurian or older (1855), perhaps equivalent to the Potsdam, Utica, and Hudson River; and later (1860) suggested that it corresponds to the Paradoxides zone in Newfoundland (see also Billings, 1860). The first edition of Acadian Geology (Dawson, 1855) places the series from Lower Silurian to Azoic; the second edition (1868) places it from the Chazy to Upper Potsdam "partly on evidence of an inferential character" (page 613). Marcou (1862) called the series Taconic.

In 1869 Hind made the first announcement of "fossils," resembling Palæotrochus major and minor (Emmons), accompanying concretions in quartzite; and upon them he based a supposed age of Upper Potsdam to Lower Calciferous. In 1870 (1870[a], 1870[b], 1870[c], 1870[d]) he described an underlying Huronian series which has proved to be a gneissoid portion of the Meguma. In 1872 Selwyn announced the discovery of Eophyton at the Ovens, near Lunenburg, and called the series Lower Silurian, equivalent to the Harlech grit and Lingula flag of Britain, now classed as Lower and Upper Cambrian.

In the third edition of Acadian Geology (1878[a]) Dawson changed his designation of age to Cambrian, but merely because he had abandoned Murchison's classification. He speaks of "such fossils as have been found in it by Selwyn, Hind, and myself and those of its extensions in

New Brunswick and Newfoundland." It may be noted in passing that the rocks referred to in New Brunswick lie across the strike of the Meguma series and have no claim to be regarded as a continuation of it, and that on the east the strike of this series swings so far south as to clear southern Cape Breton completely; hence it is most unlikely that any rocks in Newfoundland so far to the northeast are continuations of the Meguma. This opinion of the age of the series Dawson held to the last; and the practice of Canadian geologists generally and of the Geological Survey of Canada officially is to call it Lower Cambrian. Murray (1881, pages 534-535) noted strong resemblance to the gold-bearing series of Newfoundland, which is "unconformable below the Primordial," the base of which is the Aspidilla or Saint Johns slate.

Faribault (1887, page 144) regarded the Eophyton of Selwyn as inorganic, and compared the series with the Cambrian of the eastern townships of Canada and with the rocks of the Lake of the Woods region studied by Lawson. Walcott (1891) thought that part may be Cambrian, but much is older. Van Hise (1892) regarded Eophyton as organic, and hence a valid fossil, but considered the series as probably Algonkian. Becker (1895), upon the basis of literature, concluded that the series is more probably Algonkian than Cambrian. Faribault (1899) still called the rocks Lower Cambrian, and this practice has continued largely to the present.

It will be seen from this summary that most of the writers have no special evidence in favor of their opinion as to the age of the series, and that those who do present testimony employ chiefly two classes—"fossils" and lithology. It is believed by the author that neither of these has been successful in establishing a probability of the Cambrian age of the Meguma, and that whatever evidence it is possible to adduce from other sources than these two indicates a probable pre-Cambrian age.

Evidence

Graphite

Both the formations composing the series contain small amounts of graphitic material. It is rarely in distinct layers or concentrated sufficiently to have any definite shape, but is diffused in minute grains and scales. In many of the mining districts the Goldenville formation contains it in the darker slates. Waverley, especially parts of East Waverley, and Salmon river near the contact with the Devonian are examples.

In the Halifax black slate formation above, the graphite is so widely distributed that no place can well be singled out. In the southeastern part of the Caribou gold district, Halifax county, close to the contact be-

tween the two formations, graphite occurs in seams up to 3 inches in thickness parallel with the stratification. In neither formation is it characteristic of any definite horizon.

It appears, then, that graphite is useful in the present connection only as showing an abundance of life in some small form or forms, distributed throughout the time occupied by the deposition of that part of the series now open to view, and entombed in its argillaceous sediments, chiefly in the upper formation.

LIME

There is little limestone in the Meguma. Faribault mentions one horizon. At the contact between the two formations lenticular bodies can be traced intermittently from the western side of Halifax harbor eastward for many miles. This is the only horizon known and is thoroughly crystalline.

There is a large amount of calcite in the quartzites as cement—an amount great enough to offer some difficulty of explanation. The quartzites are often feldspathic; but the feldspar is chiefly orthoclase, and plagioclases and basic lime-bearing silicates show no evidence of having been abundant in the rocks from which the quartzites were formed. Indeed, the general constitution of the latter requires acid progenitors. A more probable origin for this lime would be as a deposit of fine calcareous detritus from invertebrates mingled with a preponderating volume of sand and later turned into secondary interstitial calcite. But in any case it has no definite value in the age problem.

HISTORY OF RECORDED "FOSSILS"

The record of "fossils" begins with the announcement by Hind already mentioned.

> "At Waverley the concretionary forms vary from half an inch to 4 inches in diameter. They are generally oval in shape, but sometimes round, with a depression in the center. Attached to some of them are numerous arms, all symmetrically arranged" (1869, page 62).

Palæotrochus has long since been shown to be of inorganic origin.

Of some forms found by Hind at Waverley, and presumably the same as the above, Dawson (1878, pages 82-83) gave the only specific description offered for any of the "fossils" of the series and invented for them the name *Astropolithon hindi*. The frequency with which such words as "seem" and "appear" occur in the description indicates the uncertain nature of the evidence.

The supposed land plant Eophyton, discovered by Selwyn (1872), has

FIGURE 1.—*Astropolithon hindi*, BEDFORD, HALIFAX COUNTY
Side view showing radial "arms." From Provincial Museum, Halifax

FIGURE 2.—*Astropolithon hindi*, BEDFORD, HALIFAX COUNTY
Surface view of a specimen without "arms." From Provincial Museum, Halifax

ASTROPOLITHON HINDI

been the subject of much controversy. Dawson (1878, page 82) says of the markings:

"They are of very doubtful origin, and in my judgment more akin to those trails of aquatic animals which I have named Rhabdichnites."

Faribault (1887) appears to have regarded the form as inorganic, while Van Hise (1892) considered it a true fossil. In any view of the case it has no value for determining age.

In 1891 (page 26) Dawson says of the series:

"It has unfortunately afforded no well characterized fossils. The markings called Eophyton and certain radiating bodies (Astropolithon) found in it are, however, similar to those occurring elsewhere in Lower Cambrian rocks."

Bailey mentions (1898, page 55) on the surface of quartzite at Lockeport island, Shelburne county,

"despite their highly metamorphic character, numerous well marked remains of Asteropolithon, the only evidence, if such they can be considered, of organic remains yet noticed in the Cambrian rocks of southwestern Nova Scotia."

PROBABLE INORGANIC CHARACTER OF THE FOSSILS

It is unfortunate that in these cases, as in all others of supposed fossils from the Meguma series with one exception, no illustrations have been published and no technical descriptions except the one noted from Dawson. Moreover, the authors for the most part are hesitant about accepting the forms as organic, even while mentioning them as perhaps important. But, whether the objects referred to under the names Palæotrochus, Eophyton, and Astropolithon are organic or not, they would appear to have no stratigraphic value, not being index or characteristic species or genera of any known horizons elsewhere.

Our present knowledge of natural fractures in the rocks, purely inorganic in origin, discloses a close similarity between some of these and certain of the supposed fossils. The description by Dawson could well be applied to many individuals of the type of fracture called by Professor J. B. Woodworth "discoidal joints." When it is remembered that the coarser strata of the Meguma series abound in cubical pyrite, the peculiarities of shape and staining of some of the "fossils" may be explained, as well as their presence. The weathering of pyrite involves an increase in volume and a consequent pressure upon the surrounding rock, which will account for many discoidal joints, and their shapes and topographic characteristics will depend largely upon the texture, cohesion, and homogeneity of the rock.

In passing from this subject it may fairly be considered that at the present time the "fossils" above mentioned have failed to establish their

status as organic forms, even the authors who described their occurrence having later expressed grave doubt of their validity.

Dawson (1878, page 83) noted the presence of Scolithus in loose blocks near the mouth of Saint Marys river. But this was not reported *in situ*, and the form, while more abundant in some ages than in others, is not characteristic, nor has it been proved to belong to any single species.

Bailey (1898, page 46) writes regarding western Nova Scotia:

"The only specimens we have as yet been able to obtain . . . are certain small circular or ovoidal pit-like depressions found in the black shale drift, in the vicinity of Bridgewater, in Lunenburg county, and again on the coast of the same county near Heckmans island. In outline they bear some resemblance to brachiopods of the genus Obolella or Linnarsonia, but they are lacking in markings or other distinctive features by which their nature can be definitely ascertained, and for the present at least they are unavailable as evidence."

Not only this, but as yet no specific description has established their claim as organic remains.

FOSSILS: MARKINGS AT GREENBANK, HALIFAX

A few years ago Dr H. S. Poole found some forms in the slates of Greenbank, Halifax, which resemble annelid tracks and burrows (1903, page 453). As they have not yet been described, it is impossible to refer to them here in detail, but an illustration of the slab containing them is appended. They do not appear upon examination likely to furnish any index to the age of the rocks; nevertheless they are organic, and may stand in importance above all other forms so far attributed to the series, perhaps excepting Scolithus.

CONCRETIONS

At many places in both formations concretions abound in the coarser strata.

Hind noted them at Waverley as early as 1869 (page 20). At both East Waverley and West Waverley he mapped "concretionary quartzites"; but recent study of the structure of this mining district indicates that these can hardly be the same stratum. Of the concretions he says: "They frequently resemble fossil forms, and it is subsequently shown that this quartzite is fossiliferous." It was from these beds that Palæotrochus came; but a close examination of the concretionary horizon at West Waverley in 1896 and 1897 failed to disclose any organic remains to the author.

South of Black point, near Liverpool, the strata hold concretions up to a foot in diameter, but there is no resemblance in them to distinct organic forms.

FIGURE 2. CONCRETION FROM MOOSE RIVER GOLD MINES

FIGURE 1. SLATE FROM GREENBANK, HALIFAX, WITH WORM-LIKE TRAILS OR BORINGS
Provincial Museum, Halifax

FIGURE 3.—CONCRETION FROM MOOSE RIVER GOLD MINES

FIGURE 4. MARKINGS IN QUARTZITE, LOWER ARGYLE

SPECIMENS OF SLATE AND CONCRETIONS

Concretions which appear at first sight of possible organic origin occur in the western part of the Moose River district (Woodman, 1904, page 24). It is unnecessary to redescribe them here, but it may be said that careful examination of slides failed to show the slightest organic trace.

The slates of the Halifax formation are highly altered by contact metamorphism west of the city of that name, on the shore of the harbor. As they were originally more varied in texture than most of the rocks of this group, the changes have emphasized the coarse and fine layers strongly. Near York redoubt, Halifax harbor, arenaceous strata abound in concretions up to the size of a hen egg, and isolated, although occurring persistently along the same beds. Finer sandy layers have smaller concretions closer together, often coalescing. The topography of these forms is varied, but in no case do they give evidence of organic origin or contents.

The best concretions yet found in the series by the author come from Gays River mines, locally also called Coldstream. They lie beside a brook in the horizon which marks at this place the contact of the Goldenville formation with the Lower Carboniferous gold-bearing conglomerate, the plane of their major diameters occupying the stratification planes. In appearance they are extremely regular, thickened, circular discs, averaging .3 to .5 by .2 inch. Each is clearly distinct from the inclosing slate, differing in this and other respects from concretions elsewhere in the series. The lamination of the rock bends around them, so that they stand out as eyes in the slate. Cleavage has not affected them, while rendering the adjacent layers thoroughly fissile. They are so well cemented as to withstand a strong percussion or compression. In color they are like the slate, but less greenish, and often stained copper brown from iron carbonate in the overlying conglomerate.

In the slide they appear with a comparatively clear center of quartz grains, coarser than in any other part of the mass. Surrounding this is a region of mixed quartz, calcite, kaolin, and a small amount of a grayish substance as yet undetermined. Outside of this is a ring, broadly elliptical in section, apparently of kaolin closely cemented by iron oxide. The greater ease of fracturing of the clear central part in comparison with this margin is noticeable. Adhering to the main concretion here and there are strips of the chloritic slate in which it was formed. Although apparently, when examined in the field, especially favorable as a possible resting place of fossils, these concretions have not been shown to contain any organic nucleus.

One mile south of Lower Argyle, on the west coast of the province, a ledge of slightly schistose quartzite beside the post-road has on its weathered surface pits which are of either concretionary or organic origin.

They are elliptical in outline, 2.5 to 5 inches long and 1.5 to 2.5 inches wide. Two have a slightly raised center. No structures are visible, and the forms are not such as have been described before, although in some ways similar to the mold of "Astropolithon." They may be concretionary, but the exposed surface is different from that found in weathered concretions elsewhere. They have no value as evidence at present, even though their appearance is more organic than that of most of the "fossils" from the series, and they and the concretions of Gays river are described in some detail, chiefly from the belief that nothing which may yield evidence should go unrecorded.

LITHOLOGICAL RESEMBLANCES AND BEDDED VEINS

Most of the lithological resemblances mentioned in literature have been noted already in this paper. In no case, according to the present ideas regarding correlation, can these likenesses be regarded as important at such geographical distances as have been spanned in the comparisons. The presence of stratified veins belongs to the same category of insufficient evidence. They occur to some extent in many parts of the world, in rocks varying in their age and physical characters, and their presence can no more be held to indicate the age of the country rock than can the presence of the red color in sandstones in other regions be employed as an index to the age of the formations.

Beyond these two classes of criteria—fossils and lithological resemblances—few writers have ventured in their search for the age of the Meguma series. But there are other data available, and it is believed by the author that they are more valid and important. These are chiefly (1) unconformities and the composition of younger rocks, (2) structure, and (3) accompanying igneous rocks.

UNCONFORMITIES

Unconformities which might be available for study are made by the contacts of the Meguma with various parts of the Carboniferous and with the Middle Devonian in the eastern part of the province, and in the Bear River basin of the west contacts of what has been called heretofore in literature Siluro-Devonian with a formation regarded by Bailey (1898) as part of the gold-bearing series. In the region between Torbrook on the west and the Avon river on the east are isolated areas at present considered by Messrs Fletcher and Faribault, of the Geological Survey of Canada, to belong chiefly to the Halifax formation, surrounded by strata of Silurian age. The contacts in this field have not yet been studied in sufficient detail to yield good evidence on the point in question. In the Bear River basin the lower rocks have not been proved to belong

CONTACT OF MEGUMA AND LOWER CARBONIFEROUS, GAYS RIVER GOLD MINE

to the Meguma series and present certain strong contrasts with it in lithology and history.

In the east, contacts with the Ordovician and Silurian can not be had because of intervening rocks of Devonian and Carboniferous age. In the valley of Salmon river, at the eastern end of the province, Middle Devonian adjoins the Meguma on the north, but the low topography gives no opportunities for visible contacts. As rocks containing Cambrian fossils are absent from the mainland portion of the province, it is impossible to work out relations between the Cambrian and the Meguma anywhere. Most of the remainder of the northern contact, as far west as the line of the Intercolonial railway, is with the Lower Carboniferous.

This contact is best seen in the artificial exposures at Coldstream (or Gays River mines), Colchester county, where an auriferous conglomerate has been worked intermittently for many years, the only fossil gold placer in the province. The upper strata are conglomerates and sandstones forming the southern edge of a large body of Lower Carboniferous rocks and composed chiefly of detritus from the Meguma series. The boulders include quartzite, slate, and quartz, the last perhaps 10 per cent of the whole. The difference between the composition of the boulders and the matrix is very marked, the latter being largely quartz. The cements are carbonate of lime, carbonate of iron, and iron hydroxide.

Gold of clastic origin is present in the conglomerate. The folding of the Meguma long preceded the erosion which gave the basal conglomerates above, and cleavage and jointing, well developed in the older series, stop short at the contact. The interbedded quartz veins characteristic of the Goldenville formation are present and their detritus furnishes much of the matrix of the conglomerate. The facet made by the plane of the floor of the Carboniferous and that made by the present erosion surface of the Meguma south of the margin form an angle of only a few degrees, indicating comparatively slight distortion and erosion since Lower Carboniferous time.

It will thus be seen that all the great events in the history of the series had been enacted before the deposition of this conglomerate.

COMPOSITION OF YOUNGER ROCKS

The testimony of sediments younger than the Meguma is inconclusive. The Carboniferous conglomerate contains much material from it, both igneous and sedimentary, showing that it was then in much the same condition as at present. At Salmon river the Devonian conglomerate holds pebbles of quartzite, often gneissoid, but no granite, according to Faribault (1887). In other places, however, the Devonian has much granite in its basal members. The supposed Ordovician conglomerate at Liv-

ingston contains nothing referable in any way to the Meguma; nor do any other rocks of that age.

COMPARATIVE STRUCTURES

An important line of evidence as to the age of the series relative to other rocks comes from a study of its structure and that of the other series represented in the peninsula. Most of the younger groups of rocks show traces of local east and west or northeast and southwest folding here and there. It would be surprising not to find this; for they were laid down upon the flanks of the Meguma, which stood as a landmass probably to the south, and some folding has naturally taken place roughly parallel with the old land; but of systematic orogenic types of any sort they show nothing directly comparable to that of the Meguma.

In the region of the Salmon River lakes and West river Saint Marys, the Lower Carboniferous rests on both Devonian and Meguma, and holds, especially near its base, many boulders of quartzite from the latter; it shows obscure northeast anticlines. In a few places the Devonian exhibits a tendency to east and west folding, but a vague one. For the most part its folds are unsystematic. The most pronounced lack of agreement of the Meguma folds and those of other series is in the Ordovician. Some of the geological sheets of the province issued by the Geological Survey of Canada (documents 389 and 550) show this well. There is here no parallelism between the axial directions in the two systems; but in this part of North America deposition was not markedly discontinuous from early in the Cambrian to the end of the Ordovician. Such unconformities as have been found are trifling and do not mark a hiatus sufficient to allow time for large scale orogenic disturbance. The Ordovician has none of the structural or lithological features that characterize the Meguma. There are not the north and south faults nor the even east and west folds.

The difference between the Ordovician and the Meguma in this respect is extremely important. It is not a trifling disagreement in the strike of the beds; it is the difference on the one hand between a type of orogeny characterized by remarkably persistent folds, comparable to those of the Jura and the Appalachians, and on the other hand an almost entire absence of type in the Ordovician.

Only a few periods of disturbances so severe as to warrant calling them mountain building can be found in this part of the country before the Mesozoic. The Appalachian revolution is outside the present discussion, as shown by the Lower Carboniferous contacts and contents. The next older catastrophe was the Acadian revolution, separating the Devonian from the Carboniferous throughout most of Acadia; but the Devonian

is younger than the Meguma, for it holds detritus from it, especially in the east. Earlier than this came the Taconic revolution, separating the Ordovician from the Silurian. This was moderate in the maritime provinces, but is shown by unconformity at the top of the Ordovician wherever observable. But it can not be this which effected the folding of the Meguma, for neither Silurian nor Ordovician reflects the type of folding which characterizes that series. It is true that between the catastrophic epochs named unconformities were made in Nova Scotia. These can be seen or inferred in various places between the different series of rocks lying north of the Meguma sediments; but they are not profound, nor can they be traced over any considerable distance, and in no case does either series affected by the unconformity resemble the Meguma in lithological or structural characteristics.

In all the maritime region of British North America a great unconformity separates the Cambrian and pre-Cambrian wherever they are found in contact. This is true in the eastern townships, in New Brunswick, and in Newfoundland. The very general distribution of this unconformity and the great hiatus which it represents render it probable that a similar break separates the Cambrian and pre-Cambrian in Nova Scotia, and that it is marked in this instance by the total unlikeness in appearance, and especially in orogeny, between the Ordovician and Meguma, or, to go farther afield, between the latter and the Cambrian of southern Cape Breton. Not only this, but the folding had been accomplished in the older series before the erosion interval, and this may place other phenomena in the series as pre-Cambrian, such as the formation of the bedded veins.

THICKNESS

The thickness also is too great when comparison is made with any known Cambrian in the east. It is four times as great as any of the Cambrian in eastern Canada or Newfoundland, even under the liberal definition of the term followed by Canadian writers, and it is twice as great as any known Cambrian section in the United States. In southern New Brunswick, but a comparatively short distance away, the thickness of the Cambrian is slight, although all three of its main subdivisions are represented. It is unexpected, to say the least, to find in the midst of fossiliferous sections nowhere more than 6,000 feet in thickness an enormous area nearly 30,000 feet thick and almost absolutely barren, as far as known at present.

INTRUSIVES

Another line of evidence is offered by the intrusives. Except a remarkably small number of basic dikes, no intrusives but granites and

marginal diorites are known in the Meguma strata, all abyssal and exhibiting no tendency to become rhyolitic. None of the younger rocks are thus characterized. The lavas of the Cambrian in Cape Breton are basaltic. The Ordovician has much contemporaneous volcanic material, largely basic, the most acid being a few syenites and aporhyolites and not granites. The Silurian in the eastern part of the province has a noticeable lack of intrusives, the chief ones being a narrow coast belt west of Malignant cove, and in the west the so-called diorites, regarded as originating in the great western bysmalith of Meguma granite. In the east the intrusives of the Devonian are chiefly basic. The Carboniferous is relatively free from igneous rocks, most of those that do occur lying near the margin of Silurian, Devonian, and Ordovician areas and possibly associated with the igneous masses in those strata.

Thus it appears that none of the rocks of known Paleozoic age in the province have passed through the same or a comparable history of invasion from molten matter as the Meguma. The pre-Cambrian of southern Cape Breton contains an abundance of rhyolitic material, affording the nearest approach to the igneous history of the Meguma shown by any of the Nova Scotian series.

Correlation with other Groups

Correlation of the Meguma series, direct or implied, has been made with the Saint John River slates of New Brunswick and eastern Maine, with several other unfossiliferous slate and sandstone belts of Maine and New Hampshire, with the Taconic of the Green mountains in New England and New York, with the gold-bearing slates of North Carolina, with the gold-bearing pre-Cambrian of Newfoundland, with similar slates and sandstones in the eastern townships of Canada, and with several British formations.

It may appear presumptuous to criticise such correlations without having seen in the field all the rocks compared, but certain safe conclusions can be drawn from general principles. In the first place, the age of some of the series has not yet been determined, through the absence of just such evidence as is needed in the Meguma; others have been classed as young as the Carboniferous. In the second place, thus far all correlation has been on two bases, neither of which can be regarded as adequate—similar position with reference to rocks of known age and similar lithological character. The first has no force, from the indefinite position of the Meguma itself. The second is invalid because of the great distances over which it has been obliged to do duty. The conditions under which strata similar to those of the Meguma might form are so easily repeated

in nature that general lithological resemblances should be used sparingly. They are unsafe, even within the Meguma series, and are really available only where the gap or unknown area is short. The nearest of the correlative series is many miles away; and without data now unobtainable, such as exactly similar stratigraphic relations and fossil remains, the Meguma should not at present be correlated, even roughly, with any other known series of rocks.

Conclusions

It is evident from Dawson's statement in 1878 that he had not for many years, if ever, regarded the Meguma series as really Silurian. Few have done so at any time, according to the present understanding of the limits of the Silurian, and in recent references among students of the field the series has been labeled Lower Cambrian. What tangible evidence there is upon which this opinion is based, it is difficult to discover. A few doubtful markings in the rocks, a resemblance to certain other rocks thought by the authors to be Cambrian, but in part of unknown age, an indefinite position below the adjacent Silurian and Devonian—these are the inadequate grounds for this judgment. With the exception of a few American authors, writers appear merely to have followed the lead of earlier ones, and no new evidence has been offered in support of the opinion expressed.

The conclusion here reached, from the evidence at present at hand, is that the Meguma series is probably pre-Cambrian. All the data appear to lead to this; and while one or another of them is inconclusive by itself, the evidence is cumulative and, along the line of structures and intrusions, measurably direct. Moreover, from the characteristics of the Ordovician it appears probable that the main chapters in the structural history of the series—namely, the folding and doming and the formation of the interbedded veins—were enacted in the interval before the Ordovician, and are thus at least as ancient as the Cambrian.

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RELATIONS OF RADIOACTIVITY TO COSMOGONY AND GEOLOGY [1]

BY GEORGE F. BECKER

(Presented for publication at the December meeting, 1907)

CONTENTS

INTRODUCTION

Even during the progress of a campaign, when complete information is necessarily unattainable, it is well to assemble facts and probabilities in an orderly manner, and to make a review of the situation as a guide to further action. It is as yet far too early to pronounce finally upon the part which radioactivity will eventually play in cosmogonic theories, but not too early to consider the bearing of recent discoveries on the genesis and past history of the globe. Since geologists to whom this paper is addressed can not be expected to be very familiar with radioactivity, I shall first make an attempt to sketch in outline such features of that subject as seem to me of especial interest to us; next I shall try to show under what conditions radioactive substances can come into existence, and finally discuss the geological effects which may be expected from them.

OUTLINE OF RADIOACTIVITY

Investigations in radioactivity have developed out of the study of the cathode rays and the Roentgen rays, the properties of which amazed the

[1] Manuscript received by the Secretary of the Society April 1, 1908.
This paper was not read at the meeting or presented by title, but was offered for publication and accepted by a unanimous vote of the Publication Committee.

world a dozen years ago. They were studied on the theoretical side by Mr Lorentz and Mr Larmor, and on the experimental as well as the theoretical side by Mr J. J. Thomson. These investigations have established that the atom is in fact extremely complex, consisting of corpuscles or electrons, which seem to have a constant mass from whatever substance they may be produced, this mass being about the one-thousandth part of that of an atom of hydrogen. The electrons always carry a negative charge of electricity. In an electrically neutral atom the electrons are in rapid, gyratory motion, the details of which are at least as complex as those of the planets in the solar system, and they are held together by a positive electric charge equal to the sum of the negative charges carried by the electrons. The electrons seem to have the same mass and charge as ions and to be identical with them.[2]

This electronic theory of matter, which rests on a solid basis of experiment, almost implies the possibility of disintegrating atoms. To provide for atomic stability the electrons in the atom must describe orbits such that the system is absolutely conservative, losing no energy whatever. The smallest dissipation of energy must eventually lead to disruption.

In pursuing the study of the Roentgen rays the famous French physicist, Mr Henri Becquerel, accidentally discovered a new species of rays known by his name. The effect produced by the Becquerel rays is radioactivity. He made this discovery in experimenting with pitchblende, or impure uraninite, and at his suggestion the properties of this mineral were investigated by Mr and Mrs Curie, who detected in it the new element radium.

They found that this element was present in very minute amounts in pitchblende, and that it emitted Becquerel rays in vastly greater quantities than pitchblende or than uranium. This emission proved to be an atomic property, depending, not on the state of combination, but solely on the amount of the element present. With Laborde, Mrs Curie showed[3] that radium is continuously losing energy at an astonishing rate, so that one gram of radium would spontaneously raise the temperature of 100 grams of water one degree in one hour. Here, then, is an actual case of an unstable atom undergoing resolution into something else, and therefore into at least two other atoms. In 1902 Messrs Rutherford and Soddy[4] suggested that helium might be one of the products, and in 1903 Messrs Ramsay and Soddy[5] demonstrated that helium was given off by

[2] J. J. Thomson: Electricity and matter, 1904.

[3] Comptes Rendus, vol. 136, 1903, p. 673.

[4] E. Rutherford: Radioactive transformation, 1906, p. 181. This work has been my main authority in the preparation of these notes.

[5] Nature, vol. 68, 1903, p. 246.

radium bromide, thus for the first time proving the actual derivation of one element from another. Mrs Curie and Mr Dewar [6] made confirmatory experiments on radium chloride fused and sealed in a quartz glass tube. Helium was also shown by Mr Debierne [7] to be one of the products of the activity of actinium.

It was found that a series of different but analogous radioactive substances results from the breaking up of the radium atom, and the constant association of radium with uranium suggested that radium itself forms at the expense of uranium. These facts led Messrs Rutherford and Soddy in 1902 to their disintegration theory,[8] according to which "it is supposed that the atoms of radioactive bodies are unstable, and that a certain fixed proportion of them become unstable every second and break up with explosive violence, accompanied in general by the expulsion of particles." Of these the most important are called α particles and are regarded by most investigators as molecules of helium. They are expelled at tremendous velocities, the maximum being approximately 20,000 kilometers per second, about one-fifteenth of the velocity of light. Less important are the so-called β particles, which are electrons and have only about a four-thousandth part of the mass of the α particles. They are emitted only by certain of the radioactive substances and have a velocity in some cases approaching that of light, but in spite of their velocity they possess far less energy than the helium atoms because of their minute mass. These β particles are identical with those which compose cathode rays. Of relatively small importance are the γ rays emitted by some radioactive substances. They are believed to be irregular disturbances of the ether identical in character with the Roentgen rays.

The heating effect produced by radioactive substances is almost entirely due to the dissipation of the energy of the α particles moving at the immense velocities already indicated. The excess of temperature of radium compounds above that of surrounding objects is a consequence of the arrest by other portions of the mass of α particles set free within the salt. The energy liberated by radioactive processes is of a wholly different order of magnitude from that of ordinary chemical reactions. Thus the transformation of radium emanation is accompanied by nearly 4 million times as much heat as is given out by an equal volume of hydrogen and oxygen combining to form water.

The disintegration theory implies that there is a long series of products whose general formula might be written U — n He, where n is a whole

[6] Comptes Rendus, vol. 138, 1904, p. 190.
[7] Comptes Rendus, vol. 141, 1905, p. 383.
[8] E. Rutherford: Radioactive transformation, 1906, p. 14.

number. Now the atomic weight of uranium is 238.5, the highest known, while that of helium is 4; so that if $n = 3$, the atomic weight would be 226.5. Mrs Curie's latest determination of the atomic weight of radium is 226.45; so that radium fits perfectly into the theoretical series.

In uranium minerals radium, helium, and lead are always found together, and Mr Boltwood [9] suggested that lead was probably the stable, or relatively stable, end member of the series. If so, its atomic weight should be 206.5. It is really 206.9; but this small discrepancy may well be due to lack of precision in the atomic weight of helium, which is only inferred from its density. Very possibly it may be found that the best way of determining the atomic weight of helium is to divide the difference between the atomic weights of uranium and lead by 8, which would give He $=$ 3.95. Lead has not yet been isolated from radium in appreciable quantities, but this is probably only because the quantity of radium itself available for experiment is almost infinitesimal.

According to the theory, there should be two radioactive substances yielding α particles intermediate between U and Ra and 4 between Ra and Pb. Just four products capable of emitting α particles are already known between Ra and Pb, but they have not been produced in sufficient quantities and pure enough to permit atomic weight determinations. Only one member between U and Ra has yet been discovered, and this, called ionium, was detected during the summer of 1907 by Mr. Boltwood. It is believed to be the immediate parent of radium or U — 2He. The missing link is represented by "uranium X", which emits β particles and γ rays, but no α particles capable of detection by present methods. It is considered probable that α particles may be given off from this substance, but at a velocity so low as not to ionize the gases through which they pass. In that case they would fail to affect the electrometer, which is the instrument employed to detect their presence.

The several members of the uranium lead series emit α particles at different characteristic velocities and their activities decay at different characteristic rates. The law of decay of any one of them is assuredly exponential, and observation tends to show that it is the simplest possible exponential; so that if I_t is the activity at time t, and I_0 the activity at the epoch from which time is counted, while λ is a constant,

$$I_t = I_0 \varepsilon^{-\lambda t}.$$

Here λ has a particular value for each radioactive substance. It follows that when

$$t = \log 2 / \lambda = 0.6932 / \lambda$$

[9] Philosophical Magazine, vol. 9, 1905, p. 613.

the original activity is reduced to one-half and the time of reduction to this "half value" is conveniently used to define and identify the several substances.[10] For radium the half-value period is about 1,300 years, but for uranium it is computed at no less than 1,000 million years, and one of the products of the disintegration of radium (radium A) has a half value period of only 3 minutes.

The law of decay also leads to the conclusion that in the spontaneous decay of uranium a condition of radioactive equilibrium must eventually be reached in which each component radioactive substance decays just as fast as it is replenished. Considering helium and lead as the stable end products of the process of degeneration, Mr Rutherford points out that this should afford a means of determining the age of minerals. Helium indeed might escape in some cases, but he thinks lead would accumulate and afford an accurate measure of time. Mr Boltwood has more recently discussed a number of analyses on this basis, showing that the ratio of metallic lead to metallic uranium in a mineral multiplied by 10 million should give the age in years approximately. This hypothesis of course assumes that the law of decay is a true law of nature, not an approximation; that no chemical or physical conditions modify it, and that the mineral has been subject to no external attack by which either lead or uranium could be removed. It makes the further assumption that no lead compounds were soluble in the solutions from which uranium minerals were deposited. I shall be obliged to recur to this subject.

Besides the uranium series, there are two other series of radioactive minerals the properties of which are less fully investigated. Thorium compounds, as Mrs Curie discovered, are radioactive and emit α particles which appear to have the same mass as the helium atoms expelled by radium.[11] The other end product of thorium degeneration is not certainly known, but the difference between the atomic weights of thorium and bismuth is just 24, which suggests that $Bi + He^6 = Th$. If so, however, there is one undiscovered step in the process. Actinium also yields products which emit α particles, but the atomic weight of actinium is unknown. It is thought that it may be a sort of collateral descendant of uranium.

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[10] The average life of a radioactive product is

$$\int_0^\infty e^{-\lambda t}\, dt = 1/\lambda = 1.443 \times \text{half-value period.}$$

[11] Mr R. J. Strutt has recently described a mineral from Greenland which contains much thorium, but only a trace of radium, and gives off large quantities of helium. Chemical News, November 29, 1907.

All three groups of radioactive bodies include remarkable substances, called *emanations*, which are of very great importance from the geological point of view. They are all gases which diffuse slowly into air and obey the ordinary laws of gases. They are known as radium emanation, thorium emanation, and actinium emanation. These gases are not acted on to an appreciable extent by any chemical or physical agent, and Messrs Rutherford and Soddy have subjected radium and thorium emanations to treatment such that no gas excepting one of the argon-helium family could possibly have survived.

The three emanations thus belong to the group of inert gases, which also includes xenon, krypton, argon, neon, and helium, so that in all there are eight members of the group. According to the disintegration theory, all the emanations degenerate by losing successive atoms of helium and only in this manner. The analogies expressed by the periodic law, on the other hand, would lead to the expectation either that there should be other heavy inert gases, as yet unknown, which would break down by shedding off neon and argon,[12] or, as an alternative, that the known emanations should under certain conditions emit molecules of neon and argon. The former of these hypotheses would seem a priori less probable than the second, for no group is yet known to contain more than nine elements, while eight inert gases have already been discovered. On the other hand, the supposition that the emanations may emit other light inert gases besides helium would rob the theory of radioactivity of its wonderful simplicity. It could no longer be maintained that radioactivity proceeded irrespective of chemical or physical environment.

Now Mr A. T. Cameron and Sir William Ramsay[13] have recently published papers the conclusions of which are very novel and will not be generally accepted in toto until confirmed by others. They reach results of two kinds. They *incline* to believe that they have isolated lithium, and perhaps sodium, from copper salts by radioactive processes, and this is the conclusion which has attracted most attention. To me it seems less fundamentally important and interesting than their unqualified assertion that under certain conditions argon and neon result from the degradation of radium emanation. When the emanation is dissolved in water they state that it yields almost exclusively neon, as its gaseous educt, while when a copper salt is simultaneously present in the solution, argon is the main product. As every one knows, Sir William was not

[12] Mr R. J. Strutt regards it as possible that all the light inert gases have been produced by degeneration, but that only those which produce helium now survive. The Becquerel rays and the properties of radium, 1904, p. 174.

[13] Journal of the Chemical Society, vol. 91, 1907, p. 1593.

only Lord Rayleigh's collaborator in the discovery of argon, but by himself identified terrestrial helium, and, with Mr Travers as collaborator, discovered neon, krypton, and xenon. With Mr Soddy, he was also the first to demonstrate that radium emits helium. By the methods which he developed the detection of neon and argon is not a matter of serious difficulty, and when he tells us that from water treated with radium emanation he got an uncondensable gas which gave a brilliant neon spectrum in which every line was identified by comparison with a vacuum tube containing atmospheric neon, there seems to be no room for doubt.[14] These chemists confirm once more the fact that radium emanation in an otherwise vacuous vessel, or when mixed with oxygen and hydrogen gases, yields helium as one of its products.

If argon and neon are produced under the conditions just mentioned, it would appear either that the α particles are of various kinds, according to circumstances, or that they are something different from molecules of the gaseous products. Messrs Cameron and Ramsay incline to the latter hypothesis, and suggest that the degradation of molecules of emanation is due to their bombardment by α particles, the disintegration being most complete and yielding helium under the simplest conditions, but less complete in the presence of water or copper salts, so that then heavier inert gases, argon and neon, result. This would leave the true nature of the α particles an open question. From its density and its probable position in the periodic series, Sir William thinks that radium emanation should be assigned an atomic weight of approximately 216.5.[15]

Another surprising feature of their investigation is a redetermination of the average life of radium from three experiments on the volume of emanation set free by radium bromide and radium sulphate. Their result is 236 years,[16] while Mr Rutherford, by a less direct method, obtained no less than 1,800 years.

It appears then that much remains to be done before even so brief a sketch of radioactivity as is here presented can be drawn without including uncertain features. Thus, for the present purpose, it must be considered how far facts of radioactivity which are undoubted bear upon geology. No one questions the enormous energy of radioactive transformations, which is also readily explained by the electronic theory of the atom, while the dissemination of radioactive substances in nature makes

[14] In this connection it is interesting to remember that the gases of the hot springs of Bath contain neon, the proportion of this gas being much greater than in the atmosphere.

[15] Journal of the Chemical Society, vol. 91, 1907, p. 931.

[16] Journal of the Chemical Society, vol. 91, 1907, p. 1282.

it essential for the geologist to reckon with the contribution to terrestrial heat which the dissipation of this energy involves.

Again, the gaseous nature of the emanations is indubitable, as well as that they are soluble in water, and thus a means is provided of transferring radioactivity from one geological formation to another almost without limit. The disintegration theory in its present shape can only be accepted with reserve until it is shown that Sir William Ramsay's neon and argon were not of radioactive origin, and the method which the disintegration theory affords of determining the age of minerals must be cautiously applied under checks by other methods. It seems highly probable that the "mineralizing" action of radioactive substances will be found extremely important, both in ore deposits and among a certain class of rocks.

Origin of Uranium and Thorium

The discovery of radium surprised the world, but professional chemists were astonished rather at the special properties of the "element" than at the instability of an atom. It was, to be sure, pretty generally supposed by those who were without special knowledge of chemistry that the so-called elements were independent entities, but from the days of Lavoisier and Dalton philosophical chemists have declined to pin their faith to this idea. Lavoisier himself was familiar with "radicles," or groups of atoms, which enter into combination as if they were simple substances. Ammonium, the amids, and cyanogen are familiar examples; indeed, among organic substances compound radicles are not the exception, but the rule. If elements could combine to groups which behaved like simple substances, it necessarily followed that the chemical relations of elements were not distinctive, and that substances as yet unresolved might prove complex. The idea of a fundamental relationship among the elements first gained prominence in 1815, through Prout's hypothesis, namely, that all the atomic weights were multiples of that of hydrogen, which almost amounted to assuming that hydrogen was Roger Bacon's "protyle,"[17] Urstoff, the one truly simple substance. Many of the great series of atomic weight determinations made during the first half of the nineteenth century were undertaken with the express purpose of testing Prout's hypothesis. They disproved it, but the idea of a protyle did not die. In 1851 J. Dumas[18] boldly asserted his belief in the transmutability of

[17] This term was revived by Sir William Crookes. Proceedings of the Royal Institution, 1887, vol. 12, p. 37.

[18] An address delivered at the Ipswich meeting of the British Association for the Advancement of Science, but not included in the report. See American Journal of Science, vol. 12, 1851, p. 275.

metals and metalloids, basing his opinion largely upon the analogous character of triads and other groups of elements. The hypothesis was not unfavorably received by Faraday, Grove, and W. R. Gladstone, who partook in the discussion.

Various attempts at grouping the elements finally resulted in Mendeléef's famous periodic law (1869), which enabled its author successfully to predict the properties of unknown elements (gallium, scandium, germanium) and is now everywhere received as expressing true relationships between their various fundamental properties. Such relationships would of course be inconceivable, were the "simple substances" totally independent entities.

Great attention has been excited by Sir Norman Lockyer's hypothesis, published in December, 1873. He suggested that the elements might be dissociated by heat. "On this working hypothesis," he writes, "the so-called elements not present in the reversing layer of a star will be in course of formation in the coronal atmosphere and in course of destruction as their vapor density carries them down." His hypothesis supposes the original atoms of which a star is composed to be possessed of the additional potential energy of combination, or that they are endothermic compounds, and he points out that the liberation of this energy through dissociation would prolong the period during which the star would give light.[19] Lockyer thus begins nebular history with complex atoms. He made no attempt to explain under what conditions they were formed or whence they derived their internal energy. His hypothesis has always aroused interest, but, as C. A. Young put it, "is encumbered with great difficulties and has not yet been accepted by physicists and chemists."

In January, 1873, nearly a year before Sir Norman Lockyer's lecture, Mr F. W. Clarke was daring enough to suggest the possibility of the evolution of elements. "We do not know but that the evolution of one element from another may be possible," he wrote. "These elements which seem today so diverse in character may be, after all, one in essence. Upon this theory the planets should contain more elements than the sun; the sun more than some of the more advanced among the fixed stars, and these in turn should be more highly organized than the nebulæ." [20] Mr Clarke's hypothesis has not attracted much notice, but it is entirely in line with modern results. Thus Mr J. J. Thomson, in his Silliman lectures, 1904, said in discussing the electronic theory of matter:

[19] Nature, vol. 9, 1894, pp. 411 and 429. Philosophical Transactions, vol. 164, 1874, p. 492.

[20] Popular Science Monthly, vol. 2, 1873, p. 320. For this paper Clarke was roundly denounced by a distinguished analyst, being classed with dreamers and speculators like Charles Darwin. American Association for the Advancement of Science, 1874, p. 13.

"If we regard the systems containing different numbers of units as corresponding to the different chemical elements, then as the universe gets older elements of higher and higher atomic weight may be expected to appear. Their appearance, however, will not involve the annihilation of the elements of lower atomic weight."[a]

Since 1873, as every one knows, great strides have been made in celestial spectroscopy, largely in consequence of Rowland's invention of concave gratings. It is therefore interesting to inquire the bearing of our present knowledge of the distribution of elements on the hypothesis of their evolution. It has occurred to me that the information available can be most instructively and compendiously conveyed by the help of the periodic system, as in the following table, where the cosmic distribution of the elements, arranged according to Mendeléef's classification, is indicated by typographical devices:

Classification of the Elements by the periodic System and their cosmic Distribution

Series.	0.	I.	II.	III.	IV.	V.	VI.	VII.	VIII.
1	......	H′′′-	....	....	....	....	....	....	....
2	He′′′-	Li-	Gl′	B	C′-	N′′-	O′′-	F	....
3	Ne	Na′′-	Mg′′-	Al′-	Si′′-	P-	S-	Cl-	....
4	A	K′-	Ca′′-	Sc′	Ti′′-	V′′	Cr′-	Mn′-	Fe′′- Ni′- Co′-
5	......	Cu′-	Zn′	Ga′′	Ge′	As-	Se	Br	....
6	Kr	Rb	Sr′	Y′	Zr′	Cb	Mo′	....	Ru′ Rh′ Pd′
7	......	Ag′	Cd′	In	Sn′-	Sb-	Te	I	....
8	Xe	Cs	Ba′′	La′	Ce′	....	....	....	....
9	......	....	....	....	....	....	....	....	....
10	......	....	....	....	....	Ta	W	....	Os Ir Pt
11	......	Au	Hg	Tl	Pb′	Bi	....	....	....
12	......	......	Ra	....	Th	U	....	....	....

All of the elements whose symbols are accented occur in the sun; those whose symbols have two accents have been detected in the stars of the Sirian class or the helium class. Three accents indicate components of nebulæ. The elements whose symbols are followed by a hyphen are found in meteorites.

A few comments must be made on the sources of information recorded in the table. In the gaseous nebula only helium, hydrogen, and nebelium have been detected. This last is a gas unknown on earth or in the stars, but is believed to be heavier than hydrogen (A. M. Clerke: Problems of astrophysics, p. 476). The list of elements in the helium stars and hydrogen stars includes

[a] Electricity and matter, 1904, p. 103.

all those which Miss Clerke regarded as well established, but chromium and nickel are perhaps present (ibid., p. 198). The identification of the solar elements rests chiefly on Rowland's great table of the solar spectrum, 1895 to 1897. In 1891 Rowland published a preliminary table (Johns Hopkins University circular) containing most of the elements enumerated in this paper. In the six succeeding years he was able to add only two, namely, platinum and ruthenium. Of these, platinum is represented by only one line (2,923.180), which it shares with cerium, and this seems to me insufficient evidence of platinum in the sun; but ruthenium has five lines, of which one is doubtful. Columbium (or niobium) appeared in the first list, but in the great table is represented by a single doubtful line with a wave length of 4,232.111, and I have left it out. Rowland photographed the spectrum of every element known in 1895 for comparison with the solar spectrum, excepting gallium, of which he had no specimen, and he failed to find even a doubtful trace of uranium or thorium. Mr P. G. Nutting has also been good enough to compare for me Exner and Haschek's table of the spectrum of uranium with a 30-foot reproduction of the solar spectrum, and finds no evidence of its existence. Rowland also found erbium and neodymium in the sun, but they do not appear in the table because their position in the periodic system is uncertain. Rowland did not include nitrogen in his lists, but seems to have agreed with other spectroscopists that the solar carbon lines are due to cyanogen. These lines consequently prove nitrogen just as well as carbon (Kayser and Runge, Wiedemann's Annalen, vol. 38, 1889, p. 80). Since Rowland's labors closed, gallium has been found in the solar spectrum by Messrs Hartley and Ramage, the presence of oxygen was established by Messrs Runge and Paschen, and Sir William Ramsay has identified helium in clevite. Very lately the rare element, europium, has been identified by Mr J. Lunt (Proceedings of the Royal Society, series A, vol. 79, 1907, p. 118). Coronium has also been identified in the corona of the sun (Astrophysical Journal, vol. 10, 1899, p. 306), and is believed to be a very light inert gas. It is unknown on earth or in the stars. The list of elements in meteors is that given by Sir Archibald Geikie, with the addition of helium (Young's Astronomy). Some other simple substances (lead, silver, gallium) have been announced as determinable spectroscopically in meteorites, but spectroscopic traces in an accessible substance do not seem comparable with stellar constituents observed under conditions of very much greater difficulty.

Rowland's determinations of wave lengths have been shown by Mr Kayser to be less accurate than he supposed them (Philosophical Magazine, vol. 8, 1904, p. 568), but his identifications of the elements in the sun were made by direct comparison between photographs of the solar spectrum and of the spectra of the elements, and will presumably prove correct.

In the nebulæ only helium, hydrogen, and nebulium have been identified. Nebulium which in the earlier days of spectroscopy was confounded with nitrogen, does not appear in the table, because it has not been found on earth and its place in the periodic system is unknown. The nebulæ very likely contain other elements besides the three just mentioned, but the nebulæ are excessively tenuous bodies and must also be extremely

cold, so that the simplicity of their spectra is not surprising.[22] Their luminosity is really as small as it appears, and few of them would be visible to the human eye, even if they were as close to us as the moon is. Langley determined the luminosity of the Owl nebula at a four-millionth part of that of white-hot iron. The origin of their light is uncertain. The glow may be due to electrical discharges, and thus analogous to the light produced in highly exhausted tubes of hydrogen at the temperature of liquid air, or possibly it is some unknown variety of phosphorescence. Though from association we incline to infer a high temperature when luminosity makes its appearance, the aurora of the Arctic night affords an instance of a glow vastly brighter than that of any nebula, and at the very low temperature which prevails at altitudes of some 34 miles. There is no proof that the gaseous nebulæ are devoid of solid matter, while it is strongly suspected that the white nebulæ do contain solids.

There does not seem to be the least doubt that stars are developed from nebulæ. The "helium" stars often have nebulous appurtenances and show significant spectral relations to the gaseous nebulæ. Helium stars pass by the finest gradations into hydrogen stars of the Sirian type, and these again into solar stars.[23]

In the table the known components of helium and Sirian stars, other than helium and hydrogen, are marked by two accents, and it is interesting to observe their distribution with reference to the periodic law. If a straight line be drawn from barium to iron, not a single element below the line is found in nebulæ or the two groups of stars, and of all the elements identified in these celestial bodies barium has the highest atomic weight (137.4). About a third of the elements in or above this line are found in these stars. Doubtless more stellar elements will be detected as spectroscopic research advances, but it seems probable that the additional elements will have atomic weights below that of barium rather than above it.

The chief components of the sun are shown in the table by one or more accents. A few rare earths detected in its spectrum are omitted because their positions in the periodic law are as yet unknown. It is highly probable that some of the metalloids, as sulphur and chlorine, may exist in the sun, although they are not spectroscopically evident. Even in the laboratory the spectra of the metalloids are very much obscured when metals are present in abundance. Of the 13 elements included in the last three series of the table, lead [24] alone is certainly found in the sun. The

[22] Cf. A. M. Clerke: Problems of astrophysics, 1903, p. 535.

[23] A. M. Clerke: Problems of astrophysics, 1903, p. 272.

[24] In Rowland's list of 1891 lead had but one line. In the great table, however, it has two unquestioned lines and two questionable ones.

presence of helium and lead, considered in connection with the absence of uranium, is extremely suggestive.

Meteors bring to the earth matter most of which, at all events, belongs to the solar system; it is in part of cometary origin and in all probability resembles the raw material of which the earth is built up. In the table the elements identified gravimetrically in meteorites are indicated by hyphens. Of these a few are not found in the sun or stars, namely, phosphorus, sulphur, chlorine, arsenic, antimony, and lithium. Meteorites must reach the sun, and the absence of lithium lines from the solar spectrum is surprising. Many of the elements of high atomic weight are also absent from the meteorites, or are present in quantities so small as to escape chemical analysis—all of those, in fact, whose atomic weights exceed those of antimony (120).

The plausibility of the evolution hypothesis is increased rather than diminished by the spectroscopic investigations of the last 35 years, and the relations of the cosmic distribution of elements to the periodic law add force to the suggestion. There is room in the table for just one very light, inert, or nullivalent element with an atomic weight below that of hydrogen. Possibly this protylic gas may be coronium. Assuming its existence, the facts known seem to point to an orderly and gradual development of members of the higher groups and the higher series.

The results of the electronic theory of matter add greatly to the force of the suggestion, as is apparent from the conclusion of Mr J. J. Thomson quoted above.

Radioactive phenomena strengthen the evidence immensely. Since it is now an established fact that some atoms can be resolved into at least two others, it can not be denied that under appropriate conditions the process might be reversed. This is recognized by Mr Rutherford, who considers it reasonable to suppose that under some circumstances heavy atoms were built up from the lighter and more elementary substances.[29]

These several lines of evidence shift the burden of proof from those who maintained the probability of evolution to the shoulders of those who deny it. Uranium and thorium have not been detected in the stars or the sun, even with the most powerful modern apparatus and under special scrutiny; yet in the sun numerous allied elements very rare on the earth have been identified, including cerium, lanthanum, neodymium, erbium, and europium. It seems highly improbable that if uranium and thorium existed in any quantity in the sun their spectra should fail to appear. When the reasonableness of the evolution hypothesis is considered, this

[29] Radioactive transformations, p. 194.

evidence of the absence of the radioactive elements from the sun is not merely negative. The probabilities are that these elements are built up, say from lead and helium, only in cooling stars or in planetary masses.

If uranium is assumed to be present in the stars and nebulæ, the mystery of the universe is portentously increased. Regarding uranium as compounded of lead and helium, it is substantially inevitable to suppose that it was formed under conditions in which it was stable. The only alternative is to imagine it an evanescent product of the spontaneous decomposition of still heavier atoms and then it must be assumed that these were stable. Now $Pb.He_8$ is an endothermic compound and almost incomparably more endothermic than any other except its fellow-members of the radioactive group. Its genesis, therefore, was accompanied by the absorption of a vast amount of energy locally concentrated and thus of great intensity. The cold and tenuous, gaseous nebulæ, whose density is less than that of the best laboratory vacuum, afford no mechanism for such a process. Uranium in the nebulæ would point to a precedent condensation, to a regeneration of the nebulous state from an aged solar system, such as was imagined by Immanuel Kant.[26] But such a process stands in conflict with the second law of dynamics and implies that the system is a *perpetuum mobile*. Only the discovery of fundamental laws of physics of which there is as yet no inkling would suffice to explain the presence of uranium in nebulæ.

It is the effort of science to reduce the facts of nature to their simplest expression. "From the earliest times there has been a tendency to regard varieties of matter as derivative," [27] and to seek their origin in an undifferentiated protylic substance or Urstoff, as Kant called it. It is hardly possible to think of a truly primitive nebula otherwise than as composed of protyle. From the modern point of view, the atoms of this substance would be the simplest systems of corpuscles capable of stable equilibrium, and it is not impossible that coronium satisfies this definition.

There is thus, so far as I can see, neither direct evidence that the sun is a radioactive body, nor is the hypothesis that it is radioactive inherently probable. There is also very little evidence that the meteors are radioactive. Mr L. J. Strutt [28] found substantially no radioactivity in siderites. Some of the stony meteorites show activity, but they are not known to contain uranium and thorium minerals and may well have acquired their activity from terrestrial emanations.

On earth the crystallized uranium and thorium minerals are confined, so far as is known, to the pegmatitic modifications of the granitic and

[26] Kant's Werke, Hartenstein, Leipzig, vol. 1, 1868, p. 302.
[27] A. M. Clerke: Modern cosmogonies, 1905, p. 148.
[28] Proceedings of the Royal Society, series A, vol. 77, 1906, p. 472.

syenitic rocks. The pitchblende of ore veins is not crystallized and is in all probability derived from the pegmatites by a secondary process. No andesites, basalts, peridotites, etcetera, have been found to carry uranium in weighable quantities, and there is much evidence that when freshly erupted they are not considerably radioactive.[29] Old ejecta, especially when porous, seem quite as active as average superficial rocks. That mediosilicic and subsilicic rocks at or near the surface of the earth and overlying or adjoining granitic rocks should acquire radioactivity from emanations and solutions is entirely intelligible.

Since uranium must have been stable when the minerals of which it is a chief component crystallized, the genesis of uranium must be possible under the conditions which accompany the formation of pegmatites. Now of these we know something. At a pressure of one atmosphere, silica crystallizes as quartz only below 800° centrigrade, as was shown by Messrs Day and Shepherd,[30] and Mr Mügge[31] has recently demonstrated by a new and brilliant method that the dihexahedral quartz of pegmatites could form under ordinary pressure only above 570° centigrade. Facts presented by Mr Brögger also show that granitic and syenitic rocks have formed in many cases at depths of only a few hundred meters from the surface,[32] and in any case the granitic massives, with their effusive modifications, being the least dense of rocks, are relatively superficial. These data would indicate that at temperatures of less than 1000° combined with pressures of a hundred or more kilograms per square centimeter, uranium might form under proper chemical conditions. It may therefore yet prove possible to combine lead and helium in bombs, even though neither high temperatures nor great pressures alone suffice to arrest the disintegration of radioactive substances. The attempt should be made.[33]

Radioactivity and the Earth's Age

Much the most important aspect of radioactivity is its bearing on the age of the earth. It is very plausibly held that the observed increment in underground temperatures must be due in part, and may be due in

[29] Nasini and Levi: Accad. Lincei. Rendiconti, vol. 15, 1906, p. 391, and O. Scarpa, idem, vol. 16, 1907, p. 44.

[30] American Journal of Science, vol. 22, 1906, p. 276.

[31] Neues Jahrbuch für Mineralogie, 1907.

[32] Die Mineralien der Syenitpegmatitgaenge, 1890, p. 224.

[33] Since this section of this paper was completed and communicated to colleagues, an important paper on the evolution and devolution of the elements, by Messrs A. C. and A. E. Jessup, has appeared in the Philosophical Magazine for January, 1908. In it the periodic law has been employed in somewhat the same way as here. I print my reflections without change, as an independent contribution to the subject.

great part, to this cause. In fact it has been established that a relatively thin layer of rock possessing the average radioactivity of surface rocks would suffice to maintain the observed temperature gradients indefinitely. This line of reasoning is in part supported by the discrepancy which has hitherto existed between the age of a cooling globe as found by Kelvin's application of Fourier's method and the antiquity of the ocean as is found from geological observations.

Supposing the uniform initial temperature of the globe and the thermal diffusivity of its substance known, the age by Kelvin's solution is inversely proportional to the square of the surface temperature gradient. If the age were accurately known from independent geological observations, the corresponding gradient for a cooling globe could be inferred at once, and a comparison of this with the observed gradients would show in how far the theory of cooling fails to explain the facts. A brief review of the age determinations, however, will show that they lack the precision requisite to give such a comparison value as a means of determining the part played by radioactivity.

During the last 15 or 20 years much work has been expended upon geological estimates of the duration of post-Archean time. The accumulation of strata is a gradual process proceeding *pari passu* with the degradation of land surfaces, though greatly affected by local conditions; and had we the assurance that the maximum rate of accumulation in the past were the same as the maximum rate at present, fairly accurate results would be attainable. The formations have also been studied with especial view to the rate of deposition, a variation in which might manifest itself in a number of ways. The studies referred to, however, have not disclosed any indication that the limits of variation with time are great, and to a certain extent they have been allowed for by Mr Walcott,[34] whose discussion of the data is more minute and comprehensive than any other with which I have met. In 1893 he reached the conclusion that the minimum estimate for post-Archean time is 25 to 30 million years, the maximum 60 to 70 million years, and that 45 million is the most probable. By a similar method Mr de Lapparent [35] in 1890 had estimated 67 to 90 million. In 1899 Sir Archibald Geikie [36] stated that, so far as he was able to form an opinion, 100 million years would suffice for the formation of the stratified rocks, and in 1900 Mr Sollas [37] arrived at 26½ million, assuming a constant rate of deposition. On the other hand, Mr

[34] Journal of Geology, vol. 1, 1893, p. 675.
[35] Bulletin Société de Géologie de France, vol. 18, 1890, p. 351.
[36] British Association for the Advancement of Science, 1899, p. 727.
[37] British Association for the Advancement of Science, 1900, p. 711.

Mellard Reade,[38] taking a low rate for erosion, computed a period of 95 million years since the base of the Cambrian. All of these estimates may have been more or less unconsciously influenced by Kelvin's great paper on the secular cooling of the earth, which appeared in 1862. In 1860, however, John Phillips [39] estimated that the time required for the deposition of the stratified rocks lay between 38 and 96 million years.

As the figures themselves show, the uncertainty is great, because the data are imperfect; but the premises have been derived from different regions in different ways, and the conclusion seems fairly well established that a few tens of millions of years will cover the period of sedimentation.

A radically different and very important method is due to Mr Joly, who sought to determine the age of the ocean from its sodium content on the hypothesis that this is derived at a uniform rate from the decomposition of the rocks of the land surface. In 1899 [40] Mr Joly reached 80 to 90 million years by his method, and in 1900 [41] he increased this estimate by 10 million in the course of an answer to a criticism by Mr Sollas,[42] who still thinks Joly's estimate too large by 30 or 40 million years. In 1902 Mr Mackie [43] discussed the same method in much detail. He appears to me to succeed in showing that Mr Joly's estimate is too large, and himself reaches 25 million without as, I think, justifying so great a reduction. Data are now accumulating on the composition of waters, and it will soon be practicable to apply Mr Joly's method more satisfactorily than was possible in 1900.[44]

It is noteworthy that the estimates from sedimentation (with a single exception) and those from the oceanic sodium content vary between substantially the same limits, 25 to 100 million years—wide limits truly, but better than unlimited guesses.

Years ago biologists were inclined to claim vast periods of time in which to accomplish the evolution of species, but recent investigations seem to have convinced them that the rate of evolution even today is far

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[38] Geological Magazine, vol. 10, 1893, p. 99.

[39] "Life on the earth," etcetera, 1860, p. 119. I have checked the computation. Mr Reade, in his "Evolution of the earth's structure," 1903, p. 256, is somewhat severe on Phillips for stating in his "Treatise on geology," 1839, that the average wastage in the drainage basin of the Ganges is 1/40,000 yard, which he is quoted as saying is about 1/111 of an inch. In the U. S. Geological Survey's copy of the treatise, 12mo edition, undated, but catalogued as 1837-39, the fraction given is 1/4,000 yard, and this is about 1/111 inch. The 40,000 in Mr Reade's copy is merely a misprint for 4,000.

[40] Transactions of the Royal Society of Dublin, vol. 7, 1899, p. 23.

[41] British Association for the Advancement of Science, 1900, p. 369.

[42] Mr Sollas repeats his criticism in his volume, "The age of the earth," etcetera, 1905.

[43] Transactions of the Edinburgh Geological Society, vol. 8, 1902, p. 240.

[44] Cf. Mr F. W. Clarke's "Data of geochemistry." U. S. Geological Survey Bulletin no. 330, 1908, p. 110.

from uniform, depending on the environment, and furnishes no safe guide to the lapse of time. Such studies as those of Mr de Vries on plants and of Mr Weldon on crabs show that under some circumstances specific modulation may be very rapid. Mr Walcott and Mr Sollas speak with authority, both as biologists and stratigraphers, and each expresses the conviction that his estimate from the strata is not inconsisent with the life record.

It would appear, then, that geology points to an age of the ocean which probably lies somewhere between 50 and 75 million years. For such a period there is also physical evidence wholly independent of the origin of the heat of the solar system. Sir George Darwin's studies of the earth-moon system led him to believe that the two planets parted company something over 54 million years ago.[45]

The age of the earth, considered as a cooling body, was computed by Clarence King,[46] using Kelvin's formulas under restrictions established by Mr Barus, at 24 million years, and this result was accepted by Kelvin [47] in his last paper on this great subject. The uniform initial temperature of this earth was 1,950° centigrade.

No one, I fancy, will be inclined to deny that the earth really is a cooling body of nebulous origin, and that a part of its heat is due to compression. Kant [48] in 1785 was the first to refer the heat of stellar bodies to the compression of nebulous matter, and Helmholtz [49] in 1854 was able to deal further with the subject, quantitatively in part, thanks to Joule's determination of the mechanical equivalent of heat. Once this cause of high temperatures was pointed out, its importance could not and can not be denied.

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[45] Philosophical Transactions, vol. 170, 1879, p. 511, and vol. 171, 1880, p. 882.

[46] American Journal of Science, vol. 45, 1893, p. 1.

[47] Transactions of the Victoria Institute, vol. 31, 1899, p. 11.

[48] "Die Vulcane im Monde," 1785. The earliest expression of great ideas is always a matter of interest, and I therefore translate some passages of Kant's paper: "Whence came the original heat? . . . Whence came the heat of the sun? If it is assumed (as is probable, on other grounds) that the protyle of celestial bodies was originally distributed in a vaporous state throughout the whole space in which they now move, and that they have formed according to natural laws, as first by chemical affinity, but afterwards and chiefly in obedience to universal attraction, then [Adair] Crawford's discovery points the way to a comprehension of how any temperature you please might be produced simultaneously with the genesis of celestial bodies. . . . If, as he proves, matter expanded in vapor contains far more heat, and indeed, to maintain its expansion, requires far more heat, than when condensed—in other words, when nebulous matter is compressed to stellar bodies—then the resulting globes must contan more caloric than would suffice to maintain the natural equilibrium with the caloric of surrounding space." He goes on to explain that the amount of heat generated must be a direct function of the mass of the stellar body, and adds: "In this way we should comprehend why the central body, as that of greatest mass in any system, may be the hottest, and so in every case a sun."

[49] Die Wechselwirkung der Wissenschaften, 1854.

On reviewing the papers dealing with the earth as a cooling body, however, I must confess to finding them unsatisfactory. The assumption of uniform initial temperature made by Kelvin seems to me untenable, because it leads either to earths which are tidally unstable for vast periods of time or to earths so cool that there was no fusion at all and no rearrangement of terrestrial matter by density. I have therefore investigated a somewhat more general problem,[50] the cooling of an earth in which the initial temperature increases directly as distance from the surface. The original surface temperature is supposed to be about that of the hottest recent lavas, say 1,300°, while on the basis of Mr Barus's experiments on diabase, the initial temperature at 40 miles from the surface is estimated at 1,600°. A discussion of the level of isostatic compensation, determined by Messrs Tittmann and Hayford,[51] leads to the belief that at a distance of 71 miles, or 114 kilometers, from the surface the rock temperature most closely approaches its melting point. Finally, the diffusivity is taken as that of the Calton Hill trap investigated by Forbes and Kelvin. These data lead to an earth which has been solid throughout from the moment when the surface first conjealed; it is about 60 million years old, and the present surface gradient should be 1° Fahrenheit in 77 feet (1° centigrade in 42.2 meters). This gradient seems very low; but many still lower gradients are known, and whether it is too low to be acceptable is a matter for consideration.[52] It will be observed that in this method of dealing with the problem the age is not dependent, as it is in Kelvin's solution, on the present surface gradient of temperature. The gradient here is a deduction. Since, also, the age found is in fairly good accord with the ages reached by other methods, my result for gradient is available for an approximate estimate of the relative importance of radioactivity.

The outer part of the earth is essentially a shell of massive rock several hundred miles in thickness. Roche [53] would make this thickness a sixth

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[50] Science, vol. 27, 1908, p. 227. In this paper, by an error in copying from the rough draft, the level of isostatic compensation is stated as 71 miles, or 140 kilometers. The last figure should be 114. The proper value was used in the formulas and computations.

[51] Report to general conference of the International Geodetic Association, Washington, 1906.

[52] In my solution the curvature of the earth's surface is neglected. As is well known, Mr R. S. Woodward has discussed both the free and the conditioned cooling of a sphere initially at a uniform temperature ("Annals of mathematics," vol. 3, 1887, pp. 75 and 129). Excepting for ages of thousands of millions of years, his formulas applied to the earth give the same results whether the cooling is free or conditioned. I have compared his formula and Kelvin's for a 60×10^6 year earth initially at 1307° having the diffusivity of the Calton Hill trap. The maximum difference is at a depth of 41 kilometers and amounts to less than 4°. The neglect of the curvature is thus of no consequence.

[53] Mémoire Academie de Montpellier, 1882.

of the distance to the center, and Wiechert [54] one-fifth. The cooling of the earth must depend almost wholly on the properties of this rock, and the film of detrital matter on the surface bears no greater proportion to the mass of the earth than might the coating of oxide on a hot cannon ball. Hence it seems to me that the value of diffusivity to be chosen is that of trap, and that the significant gradients are those to be found in massive rocks, not among strata. Furthermore, many causes tend to increase the gradient. Such are thermal springs, volcanic heat, dissipation of mechanical energy, chemical decomposition, and radioactivity, while only exceptionally high diffusivity in a massive rock of a given type or the neighborhood of large bodies of cold water tends to lower the gradient. What is requisite for the problem of a cooling earth is not an average gradient, but the average of unexceptionable gradients in massive rocks.

Suggestions of this character have been made by various writers, but the subject has been discussed in detail only, so far as I know, by Mr Johann Koenigsberger.[55] He has classified observations on temperature gradient and points out that those taken in nearly level regions in [relatively speaking] chemically unaltered rocks which are not recent eruptives are the most characteristic for the earth as a whole. He gives 26 such values, ranging from 1° centigrade in 27.8 meters to 1° centigrade in 37.9 meters. Five of the 26 are lower than 1° in 37 meters and average 1° in 37.7 meters or, in round numbers, 1° centigrade in 38 meters. This is equivalent to 1° Fahrenheit in 69.3 feet. Since a minimum gradient, rather than an average one, is demanded by the problem, I shall suppose this to be the normal value; and if the gradient due to cooling alone is 1° centigrade to 42.2 meters, as I find it for the 60-million-year earth, the gradient due to radioactivity and other analogous causes would be

$$\frac{1^\circ}{38^{\mathrm{m}}} - \frac{1^\circ}{42^{\mathrm{m}}.2} = \frac{1^\circ}{385^{\mathrm{m}}},$$

or almost exactly a tenth of the normal value.

No doubt this is only a rough approximation. If the earth were only 55 million years old, the other data remaining the same, the remainder attributable to radioactivity would be only 1° in 588 meters, while for a 65-million-year earth it would be 1° in 294 meters.

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[54] Göttingen Nachrichten, 1897, p. 221.

[55] Congrès géologique Internationale, tenth session, Mexico. Compte Rendu, 1907, p. 1127. In this very important paper Mr Koenigsberger shows that the temperatures in tunnels can be calculated by Fourier's law when the local topography is duly taken into account.

Again, in spite of Mr Koenigsberger's valuable classification of gradients, we need more information on the normal gradient, as he points out himself—indeed, I understand that he is making observations on the conductivity of rocks and the normal gradient.

Mr A. C. Lane [56] has discussed the gradient in Michigan and considers 1° Fahrenheit in 100 feet an average value in trap and limestone; but the neighborhood of large bodies of water modifies the applicability of this result.

On the whole, however, considering the good agreement between my results for a cooling earth and the age as computed by other means, it seems reasonable to conclude that a tenth represents the order of magnitude of the fraction of the gradient due to such causes as radioactivity, and that it very probably lies between an eighth and a sixteenth.

Geophysicists should not forget, however, that radioactivity is only one of the causes which may influence the gradient. Even relatively fresh rocks are rarely quite undecomposed, and eventually this must be taken into account. The disintegration of a gram of radium liberates millions of times as much heat as the peroxidation of a gram of ferrous silicate; but these silicates are also millions of times as abundant as is uranium.

Mention has been made above of Mr Rutherford's extremely interesting idea of determining the age of uranium minerals from the amount of helium, or preferably of the lead, which they contain, and geologists would assuredly rejoice in the discovery of a valid method of this kind. One condition of its acceptance would clearly be that it should give periods of the same order of magnitude as is indicated by purely geological data.

Now from the helium found in an analysis of fergusonite by Messrs Ramsay and Travers, Mr Rutherford [57] computes an age of at least 500 million years, and from an uranium mineral at Glastonbury, Connecticut, analyzed by Mr Hillebrand, a similar antiquity. The Glastonbury granite gneiss is equivalent to the Wilbraham gneiss of Mr Emerson,[58] who pronounces it unequivocally early Cambrian. Messrs Rice and Gregory [59] feel some uncertainty as to its age, but do not suggest a new position for it. For the present purpose, it is sufficient to regard it as at the bottom of the Cambrian. Mr Walcott's estimate of the lapse of time since the beginning of the Cambrian is nearly 28 million years, or about an eighteenth part of that suggested by Mr Rutherford.

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[56] Annual Report of the Michigan Geological Survey, 1901, p. 244.
[57] Radioactive transformations, p. 189.
[58] U. S. Geological Survey, Monograph 29, 1898.
[59] Connecticut Geological and Natural History Survey, Bulletin 6, 1906, p. 116.

Mr Boltwood [60] has computed the age of a large number of uranium minerals from their lead content. He shows that according to theory the age will be given in years to a first approximation, if the ratio of metallic lead to metallic uranium is multiplied by 10 million. In this way he gets for the age of the Glastonbury minerals 410 million years. Now, at Barringer hill, in Llano county, Texas, there is a very remarkable deposit of rare radioactive minerals, which are so abundant that they have been mined for the use of an electric lighting company. It happens that the age of the granite in which the pegmatite occurs is known. Mr Walcott [61] discovered in this county his Llano group, which belongs to the Grand Cañon series not far below the Cambrian. The granites are intrusive in these sediments. The great masses of granite which occur in western Burnet and all through Llano county belong to the same age as the strata, and Mr Walcott is careful to remark that he did not observe any rocks of undoubted Archean age in the region. A number of analyses [62] of the rare minerals of Barringer hill are available, and by Mr Boltwood's rule they give the following ages for the Llano beds:

Yttrialite, J. B. Mackintosh	11,470	million	years.
Yttrialite, W. F. Hillebrand	5,136	"	"
Mackintoshite, W. F. Hillebrand	3,894	"	"
Nivenite, Mackintosh	1,671	"	"
Fergusonite, Mackintosh	10,350	"	"
Fergusonite, Mackintosh	2,967	"	"

Mr Boltwood informs me, however, that, with the possible exception of nivenite, none of these minerals is really suitable for throwing any definite light on the question of the uranium-lead ratio for Llano county, since all of the specimens show signs of incipient or advanced alteration; but, according to theory, the state of combination is without influence on radioactivity, so that the only alterations which would affect the matter must involve the addition or abstraction of uranium or lead, and mere hydration, for example, should be without effect. The nivenite, interpreted by the rule, indicates an age 50 times as great as seems admissible from a geological standpoint and 4 times as great as the Glastonbury mineral, which would seem on geological grounds nearly coeval with it.

There seems to me a plausible explanation of the lack of accord among these minerals. Mr Brögger,[63] from his exhaustive studies of the Nor-

[60] American Journal of Science, vol. 23, 1907, p. 87.

[61] American Journal of Science, vol. 28, 1884, p. 431.

[62] Hidden & Mackintosh: American Journal of Science, vol. 38, 1889, p. 474. Hillebrand: American Journal of Science, vol. 46, 1893, p. 99, and vol. 13, 1902, p. 145.

[63] Die Mineralien der Syenitpegmatitgänge, part I, pp. 160, 164, and part II, p. 10.

wegian pegmatites, reaches the conclusion that the minerals of the thorite-orangite group, including urano-thorite, crystallize in his first phase of vein formation, that of "magmatic consolidation with the cooperation of pneumatolytic processes." In the second phase, or the "principal phase of pneumatolytic minerals," galena crystallizes out. He has observed galena in so many pegmatites that he considers it superfluous to enumerate them. Now, every one who has had much to do with minerals knows how impure most of them are; how prone to include much more than traces of whatever foreign substances may be present. Brögger's observations show that lead compounds must be soluble in the menstruum from which uraniferous minerals crystallize and indicate the probability that lead may be occluded in them as an impurity, the amount of which may vary from crystal to crystal.

In view of these facts, the proportion of helium in uranium minerals would perhaps afford a better basis than the lead content for estimates of their age. If Sir William Ramsay's determination of the life of radium is correct, Mr Rutherford's helium estimate of the age of fergusonite, referred to above, would reduce to 66 million years, which seems not geologically impossible. But I find no convincing evidence that the law of decay is so simple as is assumed. Under the conditions in which uranium compounds are stable, λ must necessarily reduce to zero. It is in the highest degree improbable that λ is a discontinuous function, and it is to the same degree probable that the law of decay fails like Boyle's law, or that λ varies with circumstances such as may have environed a mineral in a pegmatite, even though heat alone or pressure alone may be without effect upon radioactivity.

On the whole, then, the surface temperature gradients, taken in connection with the age of the earth as determined stratigraphically, or from the sodium content of the ocean, or from my theory of a cooling earth, do not indicate that the excess of temperature within the earth is due in any large measure to radioactivity. Something like a tenth of the gradient, however, may perhaps be due to this cause—a question which a more discriminating study of gradients will answer, at least in part. It does not seem to me that geologists can possibly accept the ages of minerals as determined from the uranium-helium or the uranium-lead ratios, which do not seem consistent and are far longer than stratigraphers could admit.

Distribution of Radioactivity in Depth

That radioactivity is almost universally distributed over the earth's terrestrial surface has been known for some years; indeed, as Mr Rutherford puts it, each blade of grass must be coated with an invisible deposit

of radioactivity material. A fortiori, soil and rocks must possess such a coating and also, so far as they are porous, a radioactive lining.[64] Pioneers in the study of the distribution of radioactivity were Messrs Elster and Geitel,[65] who have shown that radium is particularly abundant in clays and spring deposits. As has been mentioned, even volcanic matter, especially the porous tuffs, contain some radium, while fresh lavas contain little or none. In 1906 Mr R. J. Strutt made a very valuable series of determinations of the activity of massive rocks, meteorites, and sedimentary strata.[66] This investigation shows that granites and syenites are much more radioactive than other rocks, although some granites—for instance, that from the isle of Rum—contain very little radium. The metallic meteorites show no sensible activity, and stony meteorites only about as much as the basalts—a sixth or an eighth of that shown by the more active granular rocks. Messrs Eve and McIntosh[67] have added a number of American rocks to Mr Strutt's list and have corrected his results by means of an improved ratio between the quantities of uranium and radium existing in substances which are in radioactive equilibrium.[68] The corrected averages for Mr Strutt's igneous and sedimentary rocks are 1.7×10^{-12} and 1.1×10^{-12} or in mean 1.4×10^{-12} grams radium per gram of rock.

It is evident that the radioactivity of rocks must tend to raise their temperature and to increase any temperature gradient which they might have were radium absent. This was first pointed out in 1893 by Mr F. Himstedt.[69] In the next year Mr Rutherford[70] showed that the amount of heat indicated by Messrs Elster and Geitels' determinations of the radioactivity of soils far exceeded the average amount lost by the earth through radiation. In the same year Mr C. Liebenow[71] reached the same result independently and inferred that radium, or at least the disintegration of radium, must be confined to small depths, since otherwise the earth would be growing hotter. Within this shell the temperature would be constant if all the heat were due to radioactivity.

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[64] See J. Danne on superficial occurrences of radium; Comptes Rendus, Paris, vol. 140, 1905, p. 241, and McCoy and Ross, American Chemical Society, vol. 29, 1907, p. 1702.

[65] Phys. Zeitsch., vol. 3, 1902, p. 574; vol. 4, 1902, p. 162; vol. 5, 1904, p. 321.

[66] Proceedings of the Royal Society of London, series A, vol. 77, 1906, p. 472, and vol. 78, 1906, p. 150.

[67] Philosophical Magazine, vol. 14, 1907, p. 23.

[68] Rutherford and Boltwood found that the amount of radium associated with 1 gram of uranium during radioactive equilibrium is approximately 3.8×10^{-7} gram. American Journal of Science, vol. 172, 1906, p. 1. See also A. S. Eve, ibid., p. 4. Mr Strutt's paper was read before the appearance of this corrected ratio.

[69] Verhand. Freiburg. nat. Ges., vol. 14, 1903, p. 186, and Phys. Zeitsch., vol. 5, 1904, p. 210.

[70] Radioactivity, 1904, p. 344.

[71] Phys. Zeitsch., vol. 5, 1904, p. 625.

Early in 1906 the distribution of temperature in a globe heated exclusively by radium was discussed almost simultaneously by Mr J. Koenigsberger [72] and Mr R. J. Strutt.[73]

Mr Koenigsberger, starting from Fourier's equation for the conduction of heat in three dimensions, discusses several distributions of radium: (1) a uniform distribution throughout the globe, (2) a uniformly active shell, (3) a sphere in which the activity fades out gradually in depth, and (4) an active shell buried beneath an inactive layer of rock.[74]

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[72] Phys. Zeitsch., vol. 7, 1906, p. 297.

[73] Proceedings of the Royal Society of London, series A, vol. 77, 1906, p. 472.

[74] The partial differential equation representing the conduction of heat in a sphere is by Riemann's Partielle Differentialgleichungen, section 61:

$$\frac{d\,(ur)}{dt}=\frac{k}{c}\,\frac{d^2\,(ur)}{dr^2},$$

where u is the excess of temperature, as compared with the surface, of a point at a distance r from the center; k is the conductivity; c the thermal capacity, and t the time. If q is the quantity of heat liberated per second per cubic centimeter by radioactivity, the rate at which the temperature would rise is q/c. If the earth is in thermal equilibrium, the heat lost by conduction per unit of time must be equal and opposite to q/c. Hence

$$\frac{du}{dt}=-\frac{q}{c};$$

and since r does not vary with t,

$$r\frac{du}{dt}=\frac{d\,(ur)}{dt}=-\frac{qr}{c}.$$

Consequently

$$\frac{d^2\,(ur)}{dr^2}=-\frac{qr}{k}$$

represents the distribution of temperature in any radioactive sphere in which the radium is symmetrically distributed with reference to the center.

When q and k are constant for such a portion of the sphere as is radioactive, the integral of this expression contains two arbitrary constants. If the problem to be discussed is that of a superficial shell of radioactive matter, let R be the outer radius of the earth and R_0 the inner radius of the shell. Then du/dr must vanish, for $r = R_0$ and u must be zero at the surface or when $r = R$. The complete solution is then

$$\frac{ku}{q}=\frac{R^2-r^2}{6}-\frac{R^3_0}{3}\left(\frac{l}{r}-\frac{l}{R}\right);\quad \frac{du}{dr}=-\frac{q}{3k}\left(r-\frac{R^3_0}{r^2}\right)$$

for a sphere which is radioactive throughout $R_0 = o$ in these formulas. If, on the other hand, the shell is thin, let $R-r=x$, where x is the distance from the surface, and let $R-R_0=s$ the thickness of the shell. Then x/R will be a small quantity and the formulas reduce to the form employed by Mr Strutt and which will be used here in the text. As Mr Koenigsberger shows, q may, if desired, be regarded as a function of r; for example, q' may be a constant, such that

$$q'\,r^m=q;$$

so that the radioactivity vanishes at the center of the earth and is greatest at the surface. The differential equation may still be integrated with ease. Again, k may be supposed to vary with the temperature. I may observe, however, that it can not really vary by such a law as $k=k_0\,(l-au)$, for then when $u=l/a$, $k=0$, and this would mean that a body heated to a temperature l/a would never cool at all!

In a sphere of initially uniform temperature cooling according to Fourier's law, the temperature gradient is a maximum at the surface and decreases continuously with increasing depth. By an inadvertence, Mr Koenigsberger states that in this case the gradient increases with depth.

Mr Strutt independently reached the equation of the distribution of temperature in a thin radioactive shell uniformly charged with radium.[75] He computed the thickness of the crust at 45 miles and the temperature of the interior at 1530° centigrade, assuming a surface temperature gradient of 1° Fahrenheit in 42.4 feet. His constants have been in part superseded, and I have therefore recomputed his equations for a gradient of 1° Fahrenheit in 50 feet with the conductivity of the Calton Hill trap, 0.00415, assuming that the thermal effect of 1 gram of pure radium is 100 gram calories per hour. It follows that the thickness of the radioactive shell needful to maintain the temperature gradient is 137 kilometers if it contains 1.4×10^{-12} grams of radium per gram of rock uniformly distributed, while the resulting internal temperature would be no less than 2488° centigrade, which seems high.

As is well known, Mr Barus investigated the melting point of diabase, finding that it rose in simple proportion to the pressure. At a depth of 137 kilometers diabase would melt at about 2100° centigrade; hence a temperature of 2488° centigrade at this depth would imply a liquid couche and consequently tidal instability, which is inadmissible.

Evidently, then, there must be a limit to the effects which can be attributed to radioactivity, and with the data in hand a surface gradient of 1° Fahrenheit in 50 feet can not be accounted for in this manner. The limitations are easily determined from Mr Strutt's equations, which may be written

$$v = \frac{qx}{2k}(2s - x)\,;\quad \frac{dv}{dx} = \frac{q}{k}(s - x)$$

where v is the temperature excess; q the quantity of heat developed in the radioactive shell per cubic centimeter per second; k the thermal conductivity of the rock; s the thickness of the shell, and x the distance from the surface. The temperature at which diabase melts may be represented with sufficient accuracy by

$$y = 1170^\circ + 67.5 \times 10^{-6}x.$$

If the v curve is tangent to this diabase line at x_0, it is easy to eliminate s and show that

$$x_0 = \sqrt{2.\frac{1170k}{q}}$$

Then with the conductivity of the Calton Hill rock, 0.00415, the density

[75] When the curvature of the earth is neglected, this problem is mathematically identical with that of the heating effect of a constant electric current on a thermally insulated conducting wire. Cf. Kohlrausch, Lehrbuch der prak. Physik, 10th edition, p. 214.

2.85, and the heating effect of radium 0.02778 gram calories per gram per second,

$q = 1.4 \times 10^{-12} \times 2.85 \times 0.02778 = 0.1108 \times 10^{-12}$; $x_0 = 93.6$ kilom. The condition of tangency gives

$$\frac{q}{k}(s - x_0) = 67.5 \times 10^{-6}$$

or

$$s = 119. \text{ kilometers} = 74 \text{ miles}.$$

and when $x = s$ or for the under surface of the shell

$$v = \frac{qs^2}{2k} = 1887^\circ \text{ centigrade}.$$

Finally, when $x = o$, the surface gradient is

$$\left(\frac{dv}{dx}\right)_0 = \frac{qs}{k} = 0.0003176^\circ \text{ centigrade per centimeter},$$

or 1° Fahrenheit per 57.4 feet.

I am thus led to the striking conclusion that with the data now known any surface gradient of temperature due to uniform radioactivity alone, which exceeds 1° Fahrenheit in 57 feet, would result in tidal instability and is impossible. The utmost thickness which can be ascribed to a shell of uniformly radioactive rock is 74 miles and the highest temperature which its under surface can possess is 1887° centigrade.

The surface gradient, 1° Fahrenheit in 57 feet, or 0.03176° centigrade per meter, or 1° centigrade in 31.5 meters, is well within the range of observed gradients; but if all the heat of the earth is to be accounted for by radioactivity, it appears too low. Mr Strutt, following Prestwich, took 1° Fahrenheit in 42.4 feet as the mean, and Mr Rutherford 1° Fahrenheit in 50 feet.

As appears from the formulas, the surface gradient is simply proportional to the thickness of the shell or to s. Hence, if only a fraction of the actual gradient is due to radioactivity, the corresponding thickness of the radioactive shell can be found by simple proportion. Thus if the normal average gradient is 1° centigrade in 38 meters and the average gradient due to radioactivity is 1° in 385 meters, the values suggested on a preceding page for a 60-million-year earth, then the radioactive shell would be 9.8 kilometers, or about 6 miles, in thickness. The corresponding thickness for ages of 55 and 65 million years are respectively, in round numbers, 6 kilometers and 13 or 4 miles and 8.

While there are limitations to the possible thickness of a uniformly radioactive layer, there are also reasons for believing that radioactivity is not uniformly distributed, and that it is at a maximum not more than a few thousand feet from the solid surface of the earth.

In this connection the radioactivity of the ocean presents points of great interest. Mr Strutt [76] and Mr A. S. Eve [77] have made determinations of the activity of sea salt and Mr J. Joly [78] of abysmal sediments. Mr Eve finds that sea water does not contain per gram more than 6×10^{-16} grams radium, or only a three-thousandth part as much as Mr Strutt's igneous rocks, and he infers that the uranium denuded from the land is deposited in the oceanic sediments. Mr Joly obtained from Sir John Murray globigerina ooze from a depth of 1,990 fathoms and red clay from 2,740 fathoms. The former contained 6 times as much radium as Mr Strutt's igneous rocks and the latter 16 times as much.

The activity of the ocean itself is almost negligible. Its average depth is about 3,440 meters (Woodward) and its density 1.027 Clarke), so that the weight per square centimeter is 353,300 grams. Dividing by 3,000 gives the weight of Mr Strutt's rock, which would be radioactively equivalent, and dividing again by 16 gives the corresponding weight of Mr Joly's clay. If the density of this clay is supposed to be 2.75, it follows that the whole ocean has a radioactivity no greater than that of a layer of clay 27 millimeters, or a trifle over one inch in thickness!

If radium emanation were a permanent gas, ocean water would be charged with it, according to Henry's law; but the half-value period of radium emanation is only 4 days and its average life therefore 5.8 days. In so short a time as six days this heavy gas, liberated at or beneath the ocean bottom, would diffuse vertically through the water to a short distance only, and, since its non-volatile products appear substantially insoluble in sea water, they would subside again to the bottom. In this way it would seem that a concentration of radium D and subsequent members of the series, including lead, must take place. As a matter of fact, an extremely careful analysis [79] has been made in the laboratory of the U. S. Geological Survey of a composite sample of red clay prepared by Sir John Murray from 35 specimens, and it showed 80×10^{-6} grams lead oxide per gram of clay. If any considerable part of this lead resulted from the disintegration of radium, it is substantially certain that concentration has taken place; for the equivalent amount of radium is

[76] Proceedings of the Royal Society of London, series A, vol. 78, 1906, p. 150.

[77] Philosophical Magazine, vol. 13, 1907, p. 248.

[78] Nature, vol. 76, 1907, p. 8.

[79] F. W. Clarke: Proceedings of the Royal Society of Edinburgh, vol. 27, part iii, 1907, p. 167.

over $3\frac{1}{2}$ million times the quantity found by Mr Joly in the clay. The data, however, are too few to justify more than the qualitative conclusion that an intelligible tendency is indicated to the concentration of radioactive matter on the sea bottom. On the other hand the depth of the red clay is entirely unknown, and for that reason it seems to me impossible to judge for how long a period radioactive matter has been accumulating in the ocean.

If a continuous sheet of water is practically impermeable by radium emanation, lakes and ground water must likewise greatly interfere with the escape of this gas; and on land also, so far as ground water exists, there must be a tendency to the concentration of radioactive substances. Recent studies show that underground waters are more superficial than was formerly supposed, and that meteoric waters are not abundant below a depth of a couple of thousand feet, excepting along certain fissures. The vadose circulation proceeds in most cases with extreme slowness and its waters must interpose a formidable obstruction to the diffusion of radium emanation, or must greatly promote its disintegration within the capillary fissures of rock-masses; hence also it seems to me that there must be a concentration of radioactive matter in water-bearing rocks. If so, rocks from desert areas not associated with pegmatite should show on the whole less activity than similar rocks from moist regions; so also rocks collected in very deep mines dry at the bottom should be less active than those of the overlying wet layer, and in general radioactivity should be at a maximum in the outer moist shell of the earth. This is in line with what is known of the radioactivity of volcanic rocks, and the inference is one which ought to be tested by exploration.

Radioactive clays at the ocean bottom doubtless evolve heat in the same proportion as they would at sealevel, but the temperature effects must be inconsiderable, because the clays are soaked with very cold water. Convection currents will be stimulated to some extent by the heat evolved, and this will be the principal effect. In continental regions also the vadose circulation is equivalent to a water jacket, and radioactive heat will be carried off by the slowly moving water currents. This fact is another reason for believing that the best field for the study of the effects of radioactivity on the earth as a whole is an arid one, such as the Great basin. If the congressional appropriation for chemical and physical research were not so very small, I should endeavor to have a radioactive survey made of the region of the Grand canyon of the Colorado; but that must wait.

It appears that uranium and its disintegration products originate in the granitic rocks; that radium must be confined to a relatively thin

shell; that no gradient higher than 1° Fahrenheit in 57 feet can be accounted for by uniform radioactivity, and that average radioactivity is probably a maximum where water interferes with the escape of radium emanation. It also appears inevitable to ascribe a great part of the temperature gradient of the earth to its original heat. The whole subject would be much clearer if the origin of granite and the depth to which it extends were known.

That the granites are relatively superficial seems to be proved by their low density, the relatively small silica content of most modern effusive rocks, which must come to the surface through the granite, and finally the absence of tridymite, together with the presence of much water in the granular rocks.

If, as Kelvin believed and as it seems most rational to believe, the rocks of the earth's lithoid shell consolidated at their melting temperatures, no granitic rocks can have formed until all the others had congealed. It does not seem possible consistently to imagine a globe in the process of cooling in which a layer of freshly consolidated basalt immediately underlies a sea of granitic magma; for the basalt surface would have a temperature of 1170° plus an amount corresponding to the pressure at that particular depth, while since the inversion point of tridymite at atmospheric pressure is some 800°, the lower surface of granitic sea would have a temperature of, say, 800° plus an amount corresponding to the pressure. A temperature gap or discontinuity would exist between the two rocks. Under such conditions, if they could exist, the lower part of the granite would rapidly pass over into rhyolitic or trachytic magmas and the temperature curve would be inflected. On the other hand, I find no difficulty in imagining the earth consolidating to a surface of rhyolitic or trachytic composition similar perhaps to that which the moon now presents to our vision, but at a temperature of, say, 1300°. The surface would be white hot and the atmosphere would contain, *inter alia*, almost all of the water of the globe at a temperature nearly a thousand degrees above its critical temperature. Surely when the sun solidifies there will be such an epoch in its history, and the small density of Jupiter points to the existence of such conditions there. As soon as the surface of the earth solidified, its temperature must have sunk with great rapidity to the critical point of water (365°), and at the enormous atmospheric pressure of several hundred kilograms per square centimeter the intensely heated aqueous vapors must have acted on the rhyolitic shell with extraordinary energy. They were not only forced in under pressure, but sucked in by the shrinkage of the cooling lava. Here, then, were ideal

conditions for aqueo-igneous fusion and for the formation of granitic rocks from rhyolitic and trachytic massives.

Thus the formation of primitive granitic rocks may rationally be conceived as due to a refusion immediately following the consistentior status and extending as far from the surface as aqueous vapors could penetrate. How far that would be it is, to be sure, as yet impossible to say—a mile or two at least, it may be guessed, but probably not many miles.

The thermal relations of the formation of primeval granite, as sketched above, are complex. Aqueous vapor was condensed and united with the rhyolitic material to a magma of a lower temperature than the rock had possessed before aqueo-igneous fusion. Heat was liberated by the condensation of the vapor and the cooling of the magma, but heat was absorbed by the liquefaction of the rock. Now the absorption of heat in the dry fusion of orthoclase is small, and I know of no indication that it would be great in the aqueo-igneous fusion of granite, while the heat liberated by the condensation of aqueous vapor is, of course, enormous. Though no exact balance can be struck, it would seem as if the primeval granite must have formed very slowly indeed, unless by some means surplus energy could be potentialized. In the absence of such a disposition of the excess, granite could form only as fast as radiation from the surface reduced the temperature at internal levels to the point at which silica crystallizes as quartz. On the other hand, if energy could be potentialized within the mass, the tendency to stable thermal equilibrium would be fulfilled with comparative rapidity, and such tendencies usually involve adjustment at a maximum rate.

The bounds of legitimate hypothesis are not transgressed by supposing that the surplus energy of aqueo-igneous refusion was potentialized by the formation of uranium, and that the energy of radioactive matter thus represents a part of the original energy of the cooling globe. If so, the solidification of the primeval granite was hastened by the genesis of uranium, and the heat which now escapes from its disintegration products would have been radiated into space long since if no such complex atoms had been stable under the conditions of aqueo-igneous fusion. The earth has cooled more gradually because of an endothermic reaction, but the source of its heat is dynamic.

Although there is reason to believe that the radium content of the rocks is at a maximum in or just below the vadose waters, this does not affect the computation of the total amount of radium from the difference between the normal gradient and the gradient for a given age. This follows from the assumption that all the heat generated by the disintegration of radium is emitted from the surface and in so far its distribution

is unimportant. If, however, the amount of radioactivity diminishes with depth, the shell of radioactive matter must be thicker than that computed.[80]

Although the contribution of radioactivity to the total heat of the globe appears to be relatively small, the influence of radioactivity on geological processes may have been great. So far as the action of "mineralizers" is understood, it would seem that radioactive matter should be extraordinarily efficient. It is hard to see how any chemical or physical reaction could hang fire under the bombardment of α particles, which seems comparable to the explosion of fulminate of mercury. The influence of radium on the crystallization of artificial minerals ought to be studied, and it will be strange if it is not found useful. Mining geologists and petrographers also should endeavor to ascertain whether phenomena hitherto mysterious are not explicable by radioactivity, but they will probably meet with little success until further systematic laboratory researches have been made with the especial purpose of elucidating the subject. Unfortunately there seems no hope of this until the fundamental importance of geophysical researches is more generally appreciated.

Summary

This paper begins by an attempt to outline in sufficient detail for the use of geologists the magnificent investigations of a small group of physicists on radioactivity. While a few matters are still in doubt, these are relatively unimportant to geologists, and it is fully established that radioactivity must be taken into account in estimating the age of the earth as well as in the explanation of geophysical phenomena.

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[80] If the heat developed by radioactivity were greatest at the surface, say equal to q_0, and diminished linearly with depth, vanishing when the depth were σ, then the heat developed per cubic centimeter would be

$$q = q_0\left(1 - \frac{x}{\sigma}\right) \text{ and } \frac{d^2 v}{dx^2} = -\frac{q_0}{k}\left(1 - \frac{x}{\sigma}\right)$$

Making the temperature gradient zero when $x = \sigma$ and the temperature excess, or v, zero at the surface, the equations

$$\frac{dv}{dx} = \frac{q_0\sigma}{2k}\left(1 - \frac{2x}{\sigma} + \frac{x^2}{\sigma^2}\right);\quad v = \frac{q_0\sigma}{2k}\cdot x\left(1 - \frac{x}{\sigma} + \frac{x^2}{3\sigma^2}\right)$$

represent the distribution of gradient and temperature. The surface gradient in this case is

$$\left(\frac{dv}{dx}\right)_0 = \frac{q_0\sigma}{2k}$$

and the curvature of the temperature curve is considerably nearer the surface, because in this neighborhood d^2v/dx^2 is finite. On the other hand, at the bottom of the radioactive layer d^2v/dx^2 vanishes. In the case of a cooling globe the curvature of the excess of temperature curve is zero at the surface.

The second section deals with the origin of the radioactive elements. The distribution of elements in the universe as revealed by the spectroscope is discussed in connection with Mr Clarke's evolutionary hypothesis. The distribution, taken in its relations to the periodic law, points to the truth of the hypothesis that elements are evolved, those of highest molecular weight being the youngest and confined to cooling stars or planetary bodies. This conclusion is in line with Mr J. J. Thomson's corpuscular theory of matter and evolution is the converse of the devolution established by the Curies and Messrs Rutherford and Soddy. If uranium existed in the nebulæ, the mystery of the universe would be almost hopelessly deepened. Regarding uranium as an endothermic compound, it must be stable at certain elevated temperatures and pressures. Its association with pegmatites indicates in a general way the conditions of stability, and it is pointed out that the artificial production of radioactive substances is not a hopeless aspiration.

The bearing of radioactivity on the age of the earth is next considered. The more important estimates—geological, chemical, astronomical, and physical—are assembled, including a new calculation of the age of a cooling globe, made for this memoir, but published in detail elsewhere. This agrees well with the determination by other methods and gives about 60 million years as the age. From it may be deduced a gradient of 1° centigrade in 42.2 meters, while the best normal value of the gradient as derived from Mr Koenigsberger's discussion is 1° centigrade in 38 meters. The difference, about one-tenth of the latter, is offered as a first approximation to the terrestrial heating effect of radioactive substances. The theory that the age of minerals can be inferred from the ratio of uranium to helium or to lead is discussed and rejected.

A concluding section is devoted to the distribution of radioactivity in depth. The total heating effect is independent of this distribution, which, however, would affect the rate of increase of temperature in mines or wells, and something may possibly be learned of it by such means. Formulas for the temperatures due to various distributions have been given by Mr Koenigsberger and Mr Strutt. It is shown how that for a uniformly radioactive shell the highest surface gradient compatible with tidal stability is 1° Fahrenheit to 57 feet, while if the gradient due to radioactivity is a tenth of that due to cooling, the uniformly radioactive shell is a little less than 10 kilometers in thickness or, say, between 6 and 13 kilometers. The ocean has scarcely any radioactivity, while the abysmal red clay is intensely active. A plausible hypothesis is offered for the accumulation of radioactive matter beneath water or wet rocks. The intimate association of radium and granitic rocks leads to the considera-

tion of the conditions of the formation of primeval granite. The only origin compatible with known facts seems to be the action of superheated aqueous vapor on solid nearly anhydrous rhyolitic or trachytic rocks, producing aqueo-igneous fusion immediately after the consistentior status. This would apparently imply that the granitic shell is not more than a few miles in thickness and is consistent with the inference as to the thickness of the radioactive shell. The thermal relations seem to indicate that the formation of granite must have been excessively slow, unless by some means energy was potentialized. Now the formation of uranium potentialized an enormous amount of energy. Hence it is reasonable to believe that the formation of uranium took place at this time and at the expense of the heat of compression of the terrestrial nebula.

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CONGLOMERATE FORMED BY A MINERAL-LADEN STREAM IN CALIFORNIA[1]

BY RALPH ARNOLD AND ROBERT ANDERSON

(Read by title before the Society December 31, 1907)

CONTENTS

INTRODUCTION AND BRIEF DESCRIPTION

The purpose of this article is to describe a deposit of hard stream conglomerate that has been laid down during the late Quaternary and is still in process of formation in the valley of White creek, in the western part of Fresno county, California. This stream is a branch of Los Gatos creek, which flows southeastward from the Diablo range, the easternmost member of the Coast ranges, and enters the San Joaquin valley at Coalinga. The deposit was observed by the writers in the summer of 1907, during the progress of an investigation of the Coalinga oil district.

White creek flows from an area of serpentine and other metamorphic rocks and carries much mineral matter, which it deposits on evaporation of the water. The gravel of the valley floor is thus cemented and is changed to a solid pavement, through which the stream subsequently carves a channel, leaving the conglomerate as a terrace deposit along the sides of the valley. The cement is largely calcium and magnesium carbonates, with minor amounts of silica and iron oxide; the gravel is made up of pebbles and boulders of many kinds of metamorphic and sedimentary rocks, and the resulting conglomerate is so hard and compact

[1] Published with the permission of the Director of the U. S. Geological Survey. Manuscript received by the Secretary of the Society March 26, 1908.

that the stream in cutting it forms clean cross-sections through all the constituent materials.

Topography and Geology

The topography of the region is well shown in figure 1, plate 9. The hills in the foreground are the remnants of a great synclinal valley plain which once extended between the mountains in the distance and a similar range back of the point from which the picture was taken. Evidences of at least three terraces are preserved along the sides of the canyon which winds down the old valley. It is on the middle one of these terraces, which is usually 20 to 40 feet above the stream, and on the lower one which forms the present valley floor and stream pavement, and which is in most places a few feet above the channel of the stream, that the conglomerate occurs.

The rocks of the main ridge north of the old valley just mentioned, especially that portion in which White creek heads, belong to or accompany the Franciscan formation, being largely sedimentary strata, serpentine, glaucophane schist, and associated igneous and metamorphic rocks of late Jurassic or early Cretaceous age; the rest of the contiguous country, with the exception of a syncline of Pliocene sandstone underlying a portion of the old valley, is occupied by thick-bedded sandstone carrying huge brown concretions, and thin-bedded, dark clayey shale, both of Cretaceous age.

Description of the Deposits

White creek is a small stream and is intermittent in its lower course. In the 9 miles between the serpentine area and its junction with Los Gatos creek it descends 1,200 feet, with a fairly constant gradient of from 2 to 2½ per centum. The water is perfectly clear and, owing to the white mineral deposit that it forms upon the pebbles and boulders along its course, the water appears of a silvery white color. The white deposit and cemented gravel is not apparent toward the head of the stream, but is more and more in evidence farther down, along that part of the course where (during the dry season) the water ordinarily reaches the point of saturation with mineral matter and evaporates. In most years the creek dries up or becomes very much reduced during the summer months several miles above its confluence with Los Gatos creek. The conglomerate extends for about 5 miles along White creek, beginning at a point some 2 miles below the edge of the serpentine area, from which the mineral matter of the cement is derived, and ceases about a

FIGURE 1.—STREAM CONGLOMERATE CAPPING TERRACE

In the foreground is the bed of White creek, in which conglomerate is now forming. Photograph by the U. S. Geological Survey (Robert Anderson).

FIGURE 2.—NEAR VIEW OF A HARD LEDGE OF STREAM CONGLOMERATE

Note size of detached blocks of conglomerate as compared with man at the left in figure; also relative hardness of the terrace capping and underlying Cretaceous sandstone, as shown by the formation of caves in the latter. View looking north across White creek, 14 miles northwest of Coalinga, California. Photograph by the U. S. Geological Survey (Ralph Arnold).

STREAM CONGLOMERATE

mile above the confluence of White creek with Los Gatos creek. It is present most abundantly through the middle portion of this stretch, where it forms a pavement over the stream bed as much as 100 feet wide and terrace deposits on the sides of the valley in places as high as 40 feet above the stream. The ledge forming the terrace capping or stream bed pavement is in places 15 or more feet thick. (See figure 2, plate 9.) The width of the pavement on the valley floor was several hundred feet at the time the stream deposited the conglomerate that now forms the terrace lining the sides of the valley. The Cretaceous sandstone which underlies the capping is of less induration than the conglomerate and gives way more readily to weathering and erosion. As a result, the capping is undercut and large blocks of it break off as shown in figure 2, plate 9. Thus erosion removes the deposit more rapidly than would be natural in a formation of such hardness were it laid on a more resistant foundation.

The stream wears a smooth channel in its pavement, cutting directly through the boulders of the conglomerate as if it were a homogeneous rock and producing a polished section. In many cases a fluting of the rock has been caused by the division of the stream into several different channels. The inclusions in the rock are of all sizes and in all stages of decomposition, although the majority are hard and fresh. They include chiefly sandstone of various kinds, serpentine, syenite, chert, quartz, and shale. Among these the most prominent place is assumed by large concretions, often several feet in diameter, of extremely hard sandstone that are derived from the adjacent Cretaceous strata.

The cementing material is yellowish white in color. Although not very hard, it is firm and is present in large amount, forming a complete coating over most of the pebbles, sometimes completely filling the interspaces and sometimes leaving the rock porous. The rock varies in compactness and hardness, the cement in some places being less abundant and the inclusions roughly agglomerated. The rock gives way more readily to weathering than to stream wear, and where washed by the water it is usually of extreme hardness. It is frequently difficult to distinguish the Quaternary conglomerate from the rocks of the older formations, and the former is apt to lead to confusion for the additional reason that fossils derived from the Pliocene sandstone of the vicinity are in places included in it. In the lower course of White creek the gravelly bed is at present undergoing the process of hardening, the evaporating water leaving a white coating on the pebbles that causes them to adhere slightly and part with a harsh sound when one crunches the gravel under foot.

Origin and Deposition of the Cement

The serpentine and associated metamorphic rocks of the ridge in which White creek heads are the source of the cement which hardens the conglomerate. An analysis of similar serpentine from near the New Idria quicksilver mine in the same general metamorphic area is given below (A), and to this are added analyses of two other serpentines (B and C) and a glaucophane schist (D) from the same formation, near mount Diablo, farther north in the range.

Analyses of Serpentines and Glaucophane Schist from the Diablo Range, California[2]

A—Light green, marmolitic serpentine, New Idria, San Benito county, California. W. H. Melville, analyst. (Loc. cit., p. 246.)

B—Serpentine from near Arroyo del Cerro, Contra Costa county, California. W. H. Melville, analyst. (Loc. cit., p. 250.)

C—Friable serpentine from same locality as B. W. H. Melville, analyst. (Loc. cit., p. 249.)

D—Glaucophane-schist, Pine canyon, Mount Diablo, Contra Costa county, California. W. H. Melville, analyst. (Loc. cit., p. 247.)

	A	B	C	D
SiO_2	41.54	34.84	30.96	47.84
Al_2O_3	2.48	.42	.39	16.88
Fe_2O_3	....	6.08	5.00	4.99
FeO	1.37	1.85	2.34	5.56
MgO	40.42	30.74	33.84	7.89
CaO	....	7.02	3.81	11.15
Na_2O	....	.42	.34	3.20
K_2O	....	.07	.14	.46
H_2O at 100°	14.18	1.67	2.16	.17
H_2O above 100°	....	15.72	14.02	1.81
P_2O_5	....	.04	.02	.14
Cr_2O_3	....	.68	.78	....
NiO	.04	Trace.	Trace.	....
MnO	....	.01	.09	.56
	100.03	99.56	99.89	100.65

An analysis by Dr E. C. Sullivan shows that the cement deposited on White creek is made up principally of calcium and magnesium carbonates, with minor amounts of silica and ferric oxide. A comparison of this analysis with that of the serpentine (A) from the general area in which White creek heads makes obvious the origin of the magnesium in

[2] F. W. Clarke: U. S. Geological Survey Bulletin no. 228, 1904, pp. 246, 247, 249, 250.

the cement. There is also no doubt that at least some of the calcium is derived from the serpentine, for varieties of calcium-bearing serpentine similar to those of analyses B and C are also found in the White Creek area, together with glaucophane-bearing schists high in calcium, much like the one of analysis D. It is therefore easy to account for the presence of all of the minerals in the cement, and to imagine how they are first dissolved from their original source by the carbonated surface waters under the peculiarly advantageous subterranean conditions prevalent in a region of obviously intense alteration; how they then emerge in solution in the waters of the springs on the slopes of the serpentine ridge; and, finally, how, when evaporation has brought the water to a point of saturation, the cement is deposited on and between the pebbles and boulders of the stream bed, forming the conglomerate. A combination of magnesium and calcium carbonates dolomite[3] and silica is only slightly soluble in water under surface conditions; so that, when once deposited with the associated minerals as a hard cementing matrix between the pebbles and boulders along the stream bed, the resulting conglomerate is necessarily very resistant to erosion and permits cutting of the constituent boulders rather than removal of these rocks from the matrix when attacked by running water.

The water as it emerges from the serpentine area is clear, but decidedly hard and mineralized, as may be recognized by the taste, which is, however, not unpleasant. The gradient and rough course of the stream are such that the water is continually churned up on the rocks of the miniature rapids, dashed on the adjoining boulders, and sometimes caught in side pools. Under such conditions and in the hot dry summer climate of the region, the evaporation is rapid, and the water, which starts out from the springs along the head of the stream with possibly only a moderate proportion of dissolved mineral matter, very soon reaches a point in its course where the saturation is complete enough to cause deposition. In this connection it must be remembered that, owing to the great evaporation during the day, the flow during the latter part of the night and early morning is perceptibly greater and side pools are filled and rocks wet that later on are left unprotected. The diurnal change in temperature and flow are therefore prominent factors in causing the deposition of the cement.

The principal reason why the cementing process is not active in Los Gatos creek below the mouth of White creek is because the more easily

[3] A discussion of the properties of this mineral, together with references to a considerable number of papers relating to it, will be found on pages 480 to 490 of Dr F. W. Clarke's "Data of geochemistry," U. S. Geological Survey, Bulletin no. 330, 1908.

soluble salts in the former blend with those in the waters of the latter, producing a mixture in which the magnesium forms such a small per centum that if the cement is deposited it is of such a character as to be less coherent and more easily redissolved during the rainy season than that formed by White creek. Another reason why there are no deposits of the conglomerate now forming along Los Gatos creek (and the same conditions were probably prevalent in the past) is because along its lower course the bed is largely aggraded and the water before it reaches the point of saturation has passed into the underground channel. A practically impervious bottom, such as that of White creek where it flows on the bedrock or else on the cemented conglomerate, is necessary to the formation of the conglomerate, as it prevents the sinking of the water into the underground channel before the point of saturation is reached. It might be mentioned in this connection that wherever the base of the conglomerate was seen it was resting on bedrock.

A study of the phenomenon described in this paper makes it appear, then, that the following conditions are prerequisite to the formation of stream conglomerate of this kind: A small stream carrying in solution a high per centum of magnesium carbonate, flowing over a rough, fairly impervious bottom, with a gradient steep enough to keep the water in a constant state of agitation, and a climate that is arid, at least during a considerable portion of the year, with consequent evaporation of such rapidity as to produce a high degree of saturation in the stream before it sinks beneath the surface or is diluted by the waters of some other stream.

Topographic Importance of the Deposits

The conglomerate deposits of White creek have an important effect on the topography in building up the valley bottom of an ungraded stream and retarding the rate of erosion along the canyon bottom while erosion continues to work on the rest of the drainage area. One effect of this action is to raise the general level of White creek above that of the stream to which it is tributary. The floor of the valley of the former is now several feet above Los Gatos creek where the two join, and if the process should continue and markedly affect the lower end of White creek, as well as its middle portion, as at present it does not, the formation of a hanging valley might result. It seems likely that the deposits are being extended down stream, for the reason that when the pavement is formed absorption of water into the ground ceases and the stream confines itself in a smooth, narrow channel, which allows of less evaporation and less deposition of cement, and that therefore the length of the course along

FIGURE 1.—STREAM CUTTING RECENT CONGLOMERATE

Note cutting through of the constituent pebbles in foreground; undercutting of softer Cretaceous sandstone in middle and on right of picture; slope of the conglomerate-sandstone contact on right, indicating deposition of the former in stream trench with steep sloping sides; and finally the conglomerate-floored valley bottom, a few feet above the present stream level. View looking west up White creek, 14 miles northwest of Coalinga, California. Photograph by the U. S. Geological Survey (Ralph Arnold).

FIGURE 2.—STREAM CONGLOMERATE IN PROCESS OF FORMING

Bed of White creek, showing white crust of calcium and magnesium carbonates, etcetera, cementing the boulders and pebbles into a level pavement. Note narrow channel occupied by stream during low water in summer months. View looking up stream, 12 miles northwest of Coalinga, California. Photograph by the U. S. Geological Survey (Robert Anderson).

STREAM CONGLOMERATE

which the stream flows is increased. There is also extension of the deposits during rainy years, when most of the water evaporates lower in the course than usual.

The conglomerate is likewise of importance in forming and preserving terraces. There are three causes to which the terraces may be due, namely, intermittent uplift of the land, climatic changes, and periodic change in the rate of erosion effected by the conglomerate itself. If it be supposed that upward movement of the land has taken place in late Quaternary times, the upper terrace may be explained on the assumption that the conglomerate pavement was formed as it is at present being formed, that an uplift then occurred, causing the rate of erosion to increase until the stream had reached a stage of readjustment by cutting down to the level of the present floor, and that the deposition of the modern pavement then commenced. Or it may be supposed that a period of heavy or medium rainfall, during which the stream bed was widened and a great mass of boulders and pebbles of all sizes were gathered along its course, was succeeded by a period of aridity, during which the stream, having little power to erode and transport, became subject to evaporation and saturation with mineral matter and the gravel was cemented; and that there followed a similar alternation of periods, resulting in the cutting of the channel through the terrace pavement and the formation of the present pavement at a lower level. The conglomerate itself and its influence on erosion may be considered a third factor in the production of the terraces. The stream restricts itself by the deposition of the conglomerate in some parts of its course, the water becoming concentrated into a smooth, narrow channel through the rock itself; its rate of flow is increased; the amount of water is increased, owing to the reduction of evaporation; there is little chance for the deposition of gravel or of cement, and the previously dominant work of building up gives place in that part of the stream to erosion. When the pavement is cut through, the stream is superimposed in a sharp channel upon the softer underlying sandstone. In this formation it cuts down and gradually widens out until a flat valley bottom is restored and the process of deposition of cemented gravel is recommenced upon the new grade surface.

It is improbable that any one of these three factors is unassociated with the others in the formation of the terraces. The likelihood is greater that the terraces have resulted from a complication of causes, one or the other playing the chief part and the others acting as modifying factors.

Occurrences Elsewhere

Similar deposits of stream conglomerate have not been observed along other streams in the neighboring region, although the conditions appear to be favorable along others that head in areas of serpentine and the associated metamorphic rocks. Another instance of the formation of hard conglomerate deposits other than travertine by a stream along its bed has been noted elsewhere by the junior author. This is in the Diablo range about 100 miles northwest of White creek, along the Arroyo Mocho south of Tesla, in Alameda county, and is a very similar case in which the stream flows out of an area of serpentine and Franciscan metamorphic rocks from which springs of sweetish tasting water issue. The region is comparatively arid and the stream subject to partial drying up each year. The gravel and sand are cemented into a wide level pavement of very hard rock, which retards erosion and causes the stream to descend in a series of little waterfalls. The cement is light colored and probably similar to that of White creek.

Mr J. S. Diller has observed an instance of the cementing of stream gravel *in situ* in a way very similar to that described on White creek. It is on Swift creek, a branch of Trinity river, in northern California. The stream runs through an area of serpentine and has formed a deposit of conglomerate for several miles and cut a channel through it. The stream bed is now hardened and the process seems to be continuing. In this instance the conglomerate is formed while the stream still flows within the serpentine area. This deposit is well known by the inhabitants of the region as the "cement rock." A similar deposit exists on Stuart creek, a neighboring fork of Trinity river. O. H. Hershey has made reference to the deposit on Swift creek [4] and considers it to be typical glacial till. He describes it as "an unstratified agglomeration of boulders, cobbles, pebbles, sand, silt, and clay," and says that it contains glacially striated boulders, and that it is "slightly cemented by the large constituent of unoxidized magnesian and calcareous salts," which he believes to be derived from the glacial grinding of the serpentine, of which the deposit is largely composed.

[4] "Ancient alpine glaciers of the Sierra Costa mountains, in California." Journal of Geology, vol. viii, January-February, 1900, pp. 49-50.

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LOWER PORTION OF THE PALEOZOIC SECTION IN NORTHWESTERN NEW YORK[1]

BY H. P. CUSHING

(Read before the Society December 30, 1907)

CONTENTS

INTRODUCTION

During portions of the past two field seasons the writer has been engaged in the areal mapping of the Theresa and Alexandria Bay quadrangles in northwestern New York (Jefferson county). While the main problem was the investigation of the pre-Cambrian rocks, the importance of a careful study of the Paleozoic series was fully appreciated, since this is the region of the Frontenac axis, and since little work has been done on these rocks since Emmons studied them, seventy years ago.

Work was begun about Theresa, where the pre-Cambrian rocks and the overlying Potsdam sandstone were studied and mapped. Above the Potsdam a series of somewhat calcareous, sandy dolomites with inter-

[1] Published by permission of the State Geologist of New York.
Manuscript received by the Secretary of the Society April 1, 1908.

bedded weak sandstones was found—a series which is lithologically precisely like beds which, in the region farther east, lie between the Potsdam and Beekmantown formations and have always been regarded as "passage beds" between these two formations. The work of the first field season closed before the beds next overlying had been seen, but it was confidently expected that they would be of Beekmantown age and character, since all observers who had studied the district had described and mapped this formation as present here.

Before entering on the work of the next field season, application was made to the state geologist to, if possible, detail a paleontologist to accompany me into the field, and Doctor Ruedemann was so detailed. He had in a previous season done some sectioning and collecting along the Black river, in the Watertown region, and had thus acquired an intimate knowledge of the Trenton and Black River formations there, as well as of the upper part of the Lowville beneath, though he had published nothing on the work. Because of this we commenced work at Watertown, studying and mapping such Trenton as occurred within the limits of the Theresa quadrangle, with the underlying Black river and upper Lowville, and then carried our work northward and downward in the section. We found that the normal fossiliferous limestones of the upper Lowville passed downward into similar limestones with an ostracod fauna, and that underneath these was a large thickness of other ostracod limestones, with interbedded light-colored, impure limestones, which as a whole presented a considerable lithologic contrast to the normal Lowville, but which, if not Lowville, we were unable to correlate with either Beekmantown or Chazy rocks as known to us on other sides of the Adirondack pre-Cambrian area. We could find no sharp lithologic line between the two limestone groups, except we drew it at the upper limit of the light-colored impure beds, and it appeared to us that if we were in reality dealing with two separate formations they must of necessity be closely related ones.

At this stage the work was interrupted, our presence being required on lake Champlain, at the summer meeting of Section E. At this meeting appeared Dr E. O. Ulrich, of the U. S. Geological Survey, who had come to New York for the purpose of studying the Paleozoic section around the Adirondack region, his extensive knowledge of the rocks of similar age in many other parts of the country rendering it exceedingly desirable that he should have a first hand acquaintance with the New York type section. In this work he was accompanied by Doctor Ruedemann; hence I returned to the field alone at the close of the meeting, after arranging with them that we should meet at Watertown, when they reached that

point, and go over the section together. During the week that elapsed before they reached Watertown my work substantially completed the section. Underneath the impure limestones already noted as underlying the Lowville a series of pure limestone beds was found, which contained not only ostracods, but also other fossils in considerable number. Some of these were the same as forms occurring in the Lowville above, but many were not Lowville species. It seemed to me to be a fauna unlike any that I had ever seen elsewhere in the region, to be closely related to the Lowville fauna, and certainly to have nothing to do with the Beekmantown. It quickly developed also that this apparently new formation rested upon the formation which had been met with during the work of the previous season and which had been regarded as Potsdam-Beekmantown passage beds. Moreover, it was seen that the one formation rested upon the other with marked overlapping unconformity, magnesian limestones coming in under the fossiliferous limestones with steadily increasing thickness going westward, while the fossil limestones themselves disappeared to the east. A few localities were found which showed the contact between the two formations, exhibiting a thin basal conglomerate overlaid by calcareous sands and weak, greenish, sandy shales, and these beds seemed to appear as a constant base for the series, and to change horizon because of the overlap of the formation. It also developed that the underlying formation showed considerable and rather abrupt variations in thickness along the contact line, which could only be interpreted as due to erosion. There was no normal Beekmantown in the section and the unconformity shown seemed the most important and prominent of any yet noted within the New York Champlainic. This is not surprising when it is considered that the interval comprises the larger part of Beekmantown and Chazy time.

Here, then, were two formations separated by a prominent unconformity, both by erosion and by overlap, the lower closely connected with and grading downward into the Potsdam, the upper showing close relationship with the overlying Lowville, though it can not be said that it grades into it. I could not correlate the upper with any New York formation known to me, and it came to mind that it might represent a near-shore edge of the Stones River formation of the interior basin. The lower formation neither lithologically nor faunally was normal Beekmantown; it was closely affiliated with the Potsdam, seemed like the passage beds between the two formations farther east, required mapping as a lithologic unit separate from the Potsdam, and hence required a name—at least provisionally, until study of the fossils should more plainly set forth its relationships; so I dubbed it the "Theresa" formation, from the

township of that name, in which it is exposed in its entirety. For reasons of similar nature, the name "Pamelia" was applied to the upper formation as a provisional name for mapping purposes, to serve until time should show whether a specific designation was or was not needful for the formation.

The above results were communicated to Ulrich and Ruedemann on their arrival and the fossils were shown them, following which two days were spent in going over the section together, with further considerable collection of fossils. Their expressed conclusions were confirmative of the views above expressed as to the close relationship of the Theresa and Potsdam, the absence of the normal Beekmantown, and the probable Stones River age of the Pamelia limestone, it thus representing a formation heretofore unrecognized in the New York section.[2]

The Section

In General

A generalized section of the rocks from the pre-Cambrian up to and including the lower 50 feet of the Trenton is given in the accompanying figure, with the two unconformities also indicated. The figure also brings out the fact that two overlaps occur in the section, and that the Potsdam overlap came from the east and was on a surface which sloped in that direction, while the Pamelia overlap came from the opposite direction, or, more strictly, from the southwest, and that hence the former represents the westerly edge of a deposit in an eastern, and the latter the easterly edge of a deposit in a western basin.

Potsdam Sandstone

This is the basal paleozoic member of the region and rests upon the eroded surface of the pre-Cambrian rocks. While this surface is distinctly and often abruptly uneven, being a ridge and valley surface, the irregularities have no great vertical extent, none noted exceeding 75 feet, while the majority do not exceed 50 feet; but the thickness of the formation has not been found to be greater than 80 feet anywhere within the limits of the two quadrangles, and the general formation thins both west-

[2] This informal and somewhat lengthy introduction seems not inappropriate, even though unusual, since it serves in the first place to indicate the fortunate combination of circumstances under which the work was done, and in the second place to set forth the part played by each of us in connection with the work, the participation of Ruedemann and Ulrich really amounting to actual collaboration. Especially serviceable was Ulrich's intimate acquaintance with rocks of similar age over a wide extent of territory, giving great value to conclusions which are backed by his approval.

ward and southward, so that the thickness is not greatly in excess of the irregularity of the surface upon which it was deposited. It is therefore thickest over the old valleys and thinned over the ridges, some of whose summits it failed to overtop.

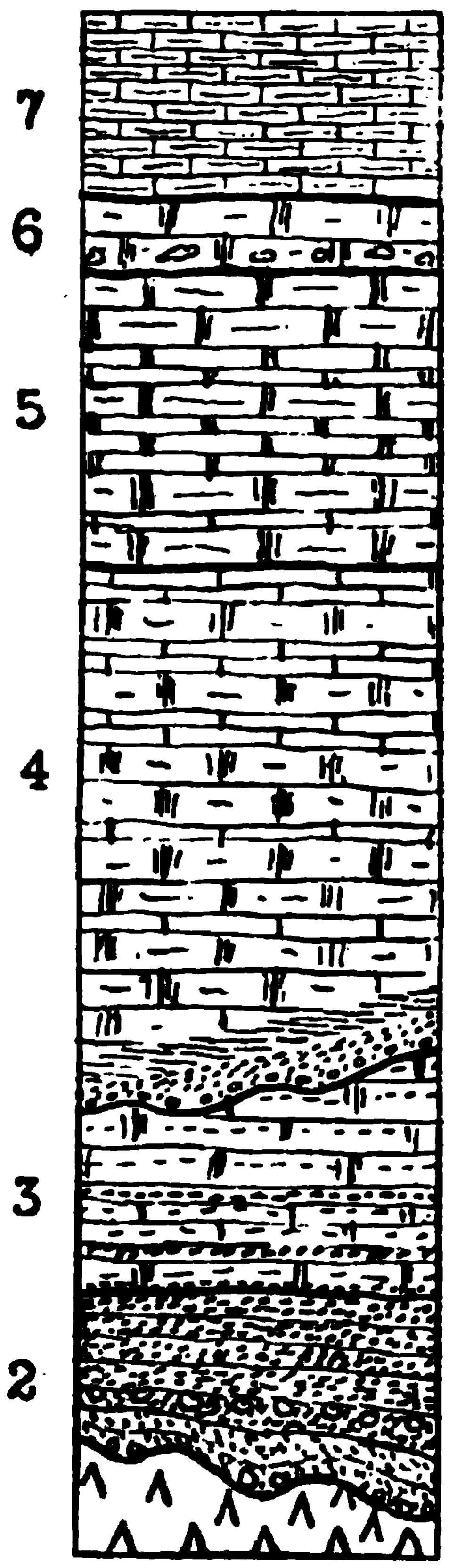

FIGURE 1.—*Generalized Section of the Rocks of the Theresa Quadrangle.*

	Feet
7. Trenton limestone. Thin bedded, black, somewhat shaly limestones, with lenses of gray, crystalline limestone.	
6. Black River limestone. Massive black limestone, lower portion full of black chert nodules	15–20
5. Lowville limestone. Blue or dove-colored fine-grained limestone, with beds of thin shaly limestones, which constitute nearly one-third of the formation	75–85
4. Pamelia limestone. Blue and dove limestone, with intercalated magnesian limestones and, in the upper half of the formation, much whitish, impure limestone and some yellow waterlime. A thin basal sandstone and overlying shales	40–130
3. Theresa formation. Somewhat calcareous, sandy dolomites, weathering to rotten stone, with interbedded weak sandstones, especially near the base..	20–60
2. Potsdam sandstone. White, yellow and red quartzose sandstone, brown spotted and weakly cemented toward the summit	0–80
1. Pre-Cambrian.	

In large part the formation consists of a nearly pure and quite thoroughly cemented quartz sand. It shows local thin conglomerates basally, which become important only in hollows of the old surface. Where the formation rests on Grenville limestone it has sometimes a calcareous cement and is weak, but there is no great bulk of rock of this sort. On the Alexandria quadrangle there occurs a stratum of very coarse conglomerate several feet in thickness, which begins and ends abruptly, has ten or a dozen feet of sandstone beneath it instead of being basal, and is a highly puzzling occurrence.[3]

[3] C. H. Smyth, Jr.: 19th Report of New York State Geologist, p. r99 and pl. 23.

The sandstone is mostly yellow to brown in color, but some is white, and near the base there is locally much red and banded red and white rock. The upper portion is more thinly and regularly bedded than the lower; cross-bedding is frequent. The lower portion is very massive and very irregularly bedded, with an obvious tendency to be influenced by the irregularities of the floor.

Toward the summit the rock becomes weaker and more friable, with frequent brown spots. The cement is in part calcareous and the brown spots seem due to the leaching out of the calcareous matter of former fossils. The summit bed is a thick but weak sandstone of this type and is full of scolithus burrows. In these upper beds linguloid shells occur in considerable abundance, though no other identifiable fossils have been seen. A large linguloid form, whose specific determination is not yet settled, is the most abundant.

In a few localities in the district small patches of no great thickness of a red sandstone are found resting on the pre-Cambrian rocks, which is much more thoroughly indurated than the normal rock and precisely resembles the red rock of the quarries of the type locality at Potsdam. Many pebbles of this rock are found in the apparent basal conglomerates of the formation here and there in the district and suggest an unconformity within the formation. Certainly a pause in deposition is indicated with induration and wear of the red rock, but with as yet no evidence as to the length of time concerned.

THERESA DOLOMITE

The Potsdam grades upward into a formation which consists of sandy dolomite layers and beds of weak brown sandstone which are mostly near the base and are quite like the upper beds of the Potsdam. The line between the two formations is drawn at the base of the first dolomite layer, but in all probability this is not a constant horizon over the district. The name given to the formation is mainly intended for local use and the necessity for its introduction arises from present doubt as to the exact equivalent of the formation elsewhere in the region.

When fresh the dolomite is a hard and tough, bluish gray rock, which, however, quickly weathers to iron-stained sandy crusts. All the beds are somewhat sandy. The most characteristic lithologic feature of the rock is the glittering calcite cleavages which appear on the freshly fractured surface. These cleavages run up to an inch in length, have a somewhat satiny luster, owing to the included sand grains, and are produced by the deposit of the calcite cement around the sand grains with similar crystallographic orientation; in other words, producing true

sand crystals on a small scale. This same lithologic peculiarity is a feature of the so-called Potsdam-Beekmantown passage beds farther to the eastward, and, so far as my observation goes, is confined to that horizon, not appearing in the Beekmantown above.

In the lower portion of the formation the large Lingula previously mentioned is abundant, a gastropod which has not yet been determined occurs at all horizons, occasional cystid plates and traces of other fossils are found, and fucoidal markings are frequent on the surfaces of some layers.

The general thickness of the formation over the quadrangle is from 60 to 70 feet. Like the Potsdam beneath, it thins to the west and apparently also to the south, though widespread sand deposits hide the decisive proof of the latter. In addition to this thinning because of overlap, it has also suffered erosion at its summit, owing to uplift (apparently slight) and wear during a lengthy time interval. For instance, it has a thickness of but 20 feet near the north end of Perch lake (see map), though recovering its normal thickness of 60 feet within a mile on each side, and the diminution in thickness is by the wearing away of the upper beds. Coincidently with this local thinning, the overlying formation thickens, showing basal beds which are lacking on each side and plainly owing their existence to the surface depression.

PAMELIA LIMESTONE

This is the most interesting formation in the section, since it represents the thinned edge of a formation which, while widespread elsewhere, has not heretofore been recognized in New York and is probably in existence in the state as a surface formation only in this immediate district. Because of its wide separation from other areas where the formation appears and because it represents only a small portion of the entire formation, the giving of a local name seems justified, and in Pamelia township the entire thickness and both contacts are exposed.

The formation consists essentially of limestone, though the bulk of it is not pure limestone. At its base is found a thickness of from 10 to 20 feet of sandstone and greenish shale, the sandstone being coarse but weak, owing to calcareous cement, and somewhat pebbly at the base, while the overlying green shales are both sandy and calcareous. Because of their weakness, these basal beds are but seldom exposed, though they seem to everywhere underlie the remainder of the formation and hence to represent a changing horizon, since the formation overlaps on the district from west to east.

The formation has a thickness of from 125 to 150 feet along the west-

ern margin of the Theresa quadrangle and somewhat less than half that thickness on the eastern border. In the former situation are several continuous sections of the lower 60 to 80 feet, but no section of the entire thickness is known and no single thick section of the upper portion. It seems superfluous to give detailed sections in this place. Above the sandy base the lower portion of the formation, 50 to 60 feet in thickness, is composed of alternating beds of blue black limestone, dove limestone, and gray magnesian limestone. The beds usually run from 1 to 3 feet in thickness, though the black limestones may reach a thickness of 10 to 15 feet. The upper half of the formation lacks the black limestone and consists of alternations of dove limestone, gray magnesian limestone, light gray to white, thin bedded, impure limestone, and yellow waterlime. About midway of this upper half is a horizon where the rocks have a pronounced pink tinge through a thickness of from 10 to 20 feet. Outside of the dove limestone beds, most of the material of this upper division is thin bedded, and the abundance of light colored layers sharply distinguishes it from the lower division. Near the summit certain layers contain abundant nodules of coarsely crystalline calcite and sometimes celestite as well. At the extreme summit are 10 to 15 feet of more massive beds of gray limestone everlaid by a thickness of a few feet of white, impure beds which are somewhat sandy, and these uppermost white beds are regarded as forming the base of the overlying Lowville formation. From base to summit the formation carries an abundant ostracod fauna. In addition, the black limestones of the lower division carry a considerable additional fauna of gastropods, cephalopods, corals, and trilobites. There is some evidence that, as the formation thins to the east, owing to overlap, these black, fossiliferous limestones occur at higher and higher horizons, in fashion similar to the rise of the basal sandstone in the same direction.

Many of the beds of dove limestone have mud-cracked surfaces. In connection with the ostracod fauna and the presence of waterlimes, this seems to indicate shallow water and closed basin conditions, similar to those which characterized the deposition of the waterlime of the Upper Silurian in the state; but the fossiliferous limestones of the lower portion of the formation indicate that a period of open water, permitting the incoming of a marine fauna, preceded the closed basin conditions.

LOWVILLE LIMESTONE

The city of Lowville is some 20 miles up the Black river from the southwest corner of the Theresa quadrangle; hence the district here is near the type locality of the formation. As exhibited within the quad-

rangle, it is a quite pure limestone formation, with a thickness of some 75 feet. The upper 20 feet are of pure limestone of blue or dove color and are exceedingly fossiliferous. Beneath follow 10 to 15 feet of thinner, more shaly limestones, with occasional fossils, after which through 30 feet thickness appear alternations of these thin layers with thicker beds of blue or dove limestone, with a basement of 10 feet of massive blue limestone, and then the white shaly beds already noted as forming the base of the formation. Ulrich suggests the probability of a slight break here between the Lowville and the underlying Pamelia, but the horizon is seldom exposed, the white beds are quite like those occurring lower down in the Pamelia formation, and the possible break has not been detected in the field. Instead the one formation seems to grade into the other, and it is a difficult matter to draw any line between them. The lower part of the Lowville formation carries mainly an ostracod fauna, other forms being scarce, though they do appear. "But the lower Lowville ostracoda include species of Leperditia and Isochilina of much larger size than any so far observed in the underlying Pamelia."[4]

BLACK RIVER AND TRENTON LIMESTONES

These represent formations deposited in a body of water which nearly or entirely surrounded the Adirondack region and hence have not the local character of the earlier deposits. The Black River limestone has its type locality in the immediate region, is about 20 feet thick, is massive and black, and its lower half is heavily charged with black chert, so that it forms an easily recognizable lithologic horizon. The Trenton is thick and has many of the characteristics that it has at the type locality, Trenton falls.

HISTORICAL

In his report, "Geology of the Second District," Emmons divides the rocks concerned into the Potsdam, Calciferous (Beekmantown), Birdseye (Lowville), Isle la Motte marble (Black River), and Trenton.[5] No detailed sections are given, but his descriptions make it clear that he includes in the Calciferous both the Theresa and Pamelia formations, except for a trifling thickness of the basal Theresa which he classed with the Potsdam. He especially notes the "drab-colored layers of the rock, which contain calcite and celestite and which are quarried for water-lime at Depauville." These form part of the light-colored, impure beds of the upper portion of the Pamelia formation. Emmons missed the

[4] Ulrich: Letter of March 25, 1908.
[5] Geology of the Second District, pp. 377-386.

unconformity between the Theresa and Pamelia formations, which is but natural, since it takes more detailed work than was then possible to disclose it. His correlation was undoubtedly made on the basis of lithologic resemblance, and he evidently had some doubts concerning it. Dr J. M. Clarke has called my attention to the fact that Emmons, in his "Fourth Annual Report," describes the Depauville waterlime as if it was then his intention to make it a formational name.[6] At the time he was evidently in doubt as to its stratigraphic position, since he states that it *overlies* the Birdseye limestone, as shown at Lafargeville (see map). As a matter of fact, the rock at Lafargeville is the fossiliferous limestone in the lower part of the Pamelia formation. In the final report Emmons does not use the name, distinctly refers the rock at Depauville to the Calciferous, and evidently would have done so in the first place had he not thought that it was above the Birdseye. In this report he nowhere refers to the rock at Lafargeville, though he maps it as Calciferous on his geologic map of the state. It seems, therefore, clear that the name was given simply because of the supposed position of the rock above the Birdseye, and was abandoned so soon as that was seen to be an error. There would seem, therefore, no reason for rehabilitating the name, especially since the rocks concerned only constitute a small part of the formation which it is proposed to call Pamelia. Either term is new to present usage, and the one chosen seems less unwieldy and more euphonious than the other and serves much better as a type locality for the formation.

In 1896 C. J. Sarle was sent into the district to map formation boundaries for the proposed new geologic map of the state. His results appear on the geologic map of 1901, but his manuscript report has never been published. His work necessitated a hurried examination of a large area and gave no opportunity for detailed study. From his manuscript it appears clear that he included the Theresa formation in the Potsdam and considered the Pamelia limestone to be Calciferous. The fossiliferous lower Pamelia, however, confused him, as it did Emmons, and he mapped it in part as Lowville; so that while the mapped patches of Calciferous in this district on the map of 1901 represent Pamelia formation, they do not represent it all. His mapping of the Theresa with the Potsdam represents an important advance over Emmons' position, since he thus puts the line between the Cambrian and Lower Silurian at the horizon of the unconformity, instead of including rocks both below and above the unconformity in the same formation (Calciferous), as was done by Emmons.

[6] 4th Annual Report, p. 324.

In his study of the pre-Cambrian rocks of the district in 1899, Smyth encountered the Theresa formation, and mapped it with and included it in the Potsdam formation, as Sarle had done, though not aware of Sarle's work and results.[7] Thus he also realized the close relationship between the two formations and the impossibility of drawing any sharp line between them.

Grabau (1906) writes of the stratigraphy of the general area, though not of the immediate district.[8] In his paper Professor Grabau is using the district as illustrative of a general proposition which he is seeking to establish. He states that at Lowville, 25 miles southeast from Watertown, "the Lowville limestone overlaps the preceding formations and rests, with a basal sandstone, upon the crystallines." He argues that the sandstone and Calciferous sandrock thinly present in the section represent an arenaceous base of the Lowville and have nothing to do with the Potsdam and Beekmantown formations. In this he is unquestionably correct, though as a matter of fact what is actually present in the Lowville section is probably the full thickness of the Lowville limestone and the thinned shore edge of the Pamelia underneath. The section here will receive further consideration later.

SUMMARY OF THE GENERAL SECTION

It appears, then, that in the district north of Watertown we have four separate lithologic units beneath the Black River limestone which require areal mapping, and that these four units are separable into two pairs of closely related formations with an intervening large unconformity, the Potsdam and Theresa formations beneath and the Pamelia and Lowville above. Eastward from the district the Potsdam sandstone may be followed as a continuous formation every step of the way to lake Champlain, with steady increase in thickness eastward, so that it attains a thickness of 1,000 feet or more in the Champlain region. Everywhere along the same line, except for a small gap in the immediate region where it is absent, owing to recent erosion, the overlying Theresa formation is also found, becoming to the eastward the so-called "passage beds" between the Potsdam and the overlying Beekmantown.[9] The Beekmantown of this northern area is sorely in need of detailed study. It certainly thickens eastward, but precise data for making comparison between the eastern and western sections are unfortunately lacking.

[7] C. H. Smyth, Jr.: 19th Geological State Report, p. 198.
[8] Bull. Geol. Soc. Am., vol. 17, pp. 584-585. Science, vol. 22, pp. 531-532.
[9] C. D. Walcott: Bulletin no. 81, U. S. Geological Survey, pp. 344-346.

From their areal distribution it is clear that these two formations represent the thinned, shoreward edges of deposits in a basin which chiefly lay to the eastward and which reached the immediate district only at the time of its greatest westward extent. This appears to be the limit of Upper Cambrian subsidence in this direction; a considerable land area to the westward which received no Potsdam and Beekmantown deposits must be postulated, and the fact that true Beekmantown deposits never even reached the district would indicate that the subsidence here persisted but a short time and was followed by low uplift, causing the shoreline to work back eastward. This tendency to a contraction of the embayment, or at least to a shifting of its shores away from the immediate region, seems to have persisted through all of Beekmantown and much of Chazy time, limiting the deposit of these formations to the east and north sides of the Adirondack region and giving rise to a low land area in the northwest district which underwent some erosion. Renewed sedimentation here was inaugurated by a depression which came in from the southwest, changing the former eastern slope of the surface to a western inclination, so that what had been the westerly shoreline of the Potsdam-Theresa bay became the easterly shoreline of this new invasion, the two overlapping slightly, so that we find here the thinned shoreward edges of both sets of formations, one above the other. The Pamelia formation was deposited in this depression, followed by the Lowville, Black River, Trenton, and Utica. Meanwhile the sea was rapidly extending itself over the whole northern New York region; so that, beginning with the Black River, we find connecting seas and similar deposits and faunas on all four sides—the first time in its geologic history that this had been the case.

THE CANADIAN SECTION

Across the river in Canada more erosion has taken place than on the New York side, because of which the pre-Cambrian isthmus which connects the Adirondack mass with the Canadian protaxis is broader, and the deposits of the earlier eastern and later western basins are not found in juxtaposition as they are in New York. On the east side of the isthmus the Potsdam sandstone is found resting on the crystalline rocks, beyond which follow in succession the normal deposits of the eastern basin—Beekmantown, Chazy, Lowville, etcetera—as one passes northeastward. On the west side of the isthmus, around Kingston, is a basal sandstone with calcareous cement, the Rideau sandstone of Ami, above which is a small thickness of impure, reddish limestones, followed by the

Lowville and Black River.[10] These are unquestionably the deposits of the western basin. The Rideau sandstone represents the basal Pamelia sandstone. Only the thinned edge of the Pamelia limestone formation appears here, if indeed it really occurs at all, which is to be expected, since the invasion came from the south. On the other hand, the impure reddish limestones, as the writer has seen them about Kingston, correspond excellently lithologically with the pinkish beds in the upper division of the Pamelia and are quite unlike any of the Lowville formation on the New York side. It may well be, therefore, that there is actually present here a thinned edge of the Pamelia formation, in which case Ami's correlation of the Rideau sandstone with the Chazy would be nearer the mark than the Black River age assigned to it by Wilson and Grabau.[11]

Sections along the Black River

Following up the Black River from the southeast corner of the Theresa quadrangle, the trend is southeast, the south line of the Potsdam embayment is soon crossed, and the Potsdam and Theresa formations disappear. The direction is first east, or toward the supposed Pamelia shoreline, and then south-southeast parallel with it. It is not yet certain whether any of the Pamelia formation occurs up the valley, or whether the Lowville rests directly on the pre-Cambrian. The nearest approach to detailed work in the district known to the writer is the work of Sarle in 1896 for the geologic map. From his manuscript the following statements are taken:

"Three miles below Carthage the base of the Birdseye (Lowville) and the Calciferous sandrock (Beekmantown) are exposed. In excavating a wheel pit for a paper mill at this point, rock was removed to a depth of 6 feet below the river level, the last 4 feet being a gritty sandstone of uniform texture, weathering to a green or dull red color. This probably represents the upper beds of the Potsdam. North of the paper mill a cut made in laying a branch of the Clayton railroad exposed the upper layers of the Calciferous sandrock. From the material of this excavation several specimens of ostracods were obtained."

Carthage lies 10 miles southeast of Leraysville, which is on the Pamelia formation near the east edge of the Theresa sheet (see map). Sarle's descriptions certainly suggest that his Potsdam is the Pamelia sandstone and his Calciferous the upper impure Pamelia limestone with its ostracod

[10] Bull. Geol. Soc. Am., vol. 13, pp. 517, 518.
[11] Canadian Record of Science, vol. ix, p. 132. Bull. Geol. Soc. Am., vol. 17, p. 584.

fauna, though it is possible that the horizon may be the lower Lowville. Identification of the ostracods would settle the question:

> "Two miles above Port Leyden is a railroad cut through a rock which corresponds to the Calciferous in horizon. This rock is thick bedded in the upper part and is generally tinged with a pinkish color. The probable line of demarcation between this and the Birdseye limestone is a band of friable sandstone of a dingy color."

Port Leyden is some 45 miles up the river from Carthage, the direction about south-southeast. The interval is so great that correlations are unsafe, but the description recalls at once the pinkish beds of the upper Pamelia and the similar beds underneath the Lowville in Canada.

Between Port Leyden and Carthage, Sarle notes several localities where the "Calciferous" is exposed and three where the underlying "Potsdam" is seen. On Roaring creek, near Martinsburg (just south of Lowville and midway between Port Leyden and Carthage), he notes a continuous section down to the gneiss and estimates thickness as follows: Black River limestone, 10 feet; Lowville, 40 to 45 feet; Calciferous, 20 feet, and Potsdam sandstone, 4 feet. The latter is dark red and has a calcareous cement.

In his paper Sarle's estimates of thickness are generally underestimates. If the thickness of the Lowville as given is accurate, then the added thickness of the underlying "Calciferous" and "Potsdam" gives a total thickness which is quite comparable with the thickness of the Lowville in the Theresa section; but if this thickness is underestimated, it is most probable that his underlying beds really represent the thinned edge of the Pamelia formation. Unless the Lowville changes much in character in the interval between Lowville and Watertown, no one would ever think of calling any of it "Calciferous," even though expecting to find that formation underneath the Lowville, whereas much of the Pamelia is lithologically quite like much of the Beekmantown. If the Pamelia be present, it has unquestionably a thickness of but a few feet, so that its basal sandstone has risen in horizon nearly to the base of the Lowville. The formation has, however, thinned to 50 feet on the eastern margin of the Theresa quadrangle.

The fact that for so many miles along the Black river, namely, from Carthage to Port Leyden, the section seems substantially the same, the full thickness of the Lowville, with a few feet of possible Pamelia beneath, and then the basal sandstone, would seem to indicate that the valley here follows closely the trend of the old shoreline of the Pamelia sea, and that, if Sarle's estimate be correct, we have a thickness of some 25 feet of the Pamelia formation along it. At right angles to this line

the formation should thicken westward and thin out to zero in the opposite direction. Its presence in force to the west is no doubt indicated by the great thickness of limestone underneath the Utica, which is reported in all the deep wells of that general area. The prolongation of this line northward beyond Carthage would lie about 5 miles east of Leraysville on the east edge of the Theresa sheet. About Leraysville the Pamelia thickness is some 50 feet, which is increased to about 125 feet on the western edge of the quadrangle. This rate of change in thickness would just about reduce the 50 feet thickness at Leraysville to the assumed 25 feet thickness shown along the river valley in the distance of 5 miles east from Leraysville to the prolongation of this line.

Age of the Theresa and Pamelia Formations

It has been argued that the Potsdam of this district is necessarily of more recent date than the Potsdam of the Champlain region, since the Potsdam deposits progressively encroached from east to west on a slowly sinking floor; hence that, while the Potsdam of the immediate region was being laid down, Beekmantown dolomites were forming on the Champlain meridian. While within certain limits this is no doubt true, it is quite possible to unduly emphasize the difference in age. The Potsdam is a continuous formation from one district to the other and carries the same fauna throughout in its upper portion. It is everywhere overlaid by the passage beds of the Theresa formation, up into which some of its fossil forms run. To the writer it has long seemed that the universal upward gradation of the Potsdam into the Beekmantown rendered it exceedingly improbable that the line between the Cambrian and Lower Silurian systems was properly drawn at this horizon, and this view has been emphasized for some time in correspondence with the State Geologist's office. The same omnipresent relations between the two formations in Canada forced Ells to a similar conclusion, though his method of avoiding the difficulty was by moving the Potsdam up into the Lower Silurian.[12]

The writer's argument has been that at least some portion of the Beekmantown should be classed with the Potsdam as Saratogan or Upper Cambrian. It was realized that in those portions of basins of subsidence remote from shorelines lack of breaks between systems might well occur; but the deposits in question in northern New York were all laid down at the edges of basins and near shorelines, and it seemed that in such situations breaks between formations should be the rule.

[12] Transactions of the Royal Society of Canada, 1894, section iv, pp. 21-30.

In their work in the Champlain valley the past season Ulrich and Ruedemann detected an unconformity *within* the Beekmantown at the summit of Brainerd and Seely's Division A, and are disposed to argue that this lower division should be separated from the rest of the formation and classified in the same system as the Potsdam beneath, making the Lower Silurian commence with Division B of the Beekmantown. With this conclusion the writer heartily agrees, and regards the argument as to the Beekmantown age of the Potsdam sandstone of the Theresa district as sound only in so far as the correlation is made with the beds of Division A which are below the break and which are regarded as not properly Beekmantown at all. The Potsdam and Theresa formations are regarded as closely related and as to be classed in the same system. How far west up the Saint Lawrence valley the true Beekmantown deposits extended is not known, but it does not appear that they ever reached the Theresa district.

The correlation of the Pamelia formation is entirely due to Ulrich and the evidence will be set forth by him. He regards it at present as equivalent to the whole or a part of the upper division of the Stones River formation, as shown in the Chambersburg, Pennsylvania, quadrangle, where the entire formation has a thickness of some 800 feet, and consists of lower, middle, and upper divisions.[13] Lest this reference should seem to make it equivalent to the Lowville, it should be noted that Ulrich no longer regards the Lowville as of upper Stones River age, but puts it above that formation, his present view being that the upper Stones River of the Chambersburg section, with which he correlates the Pamelia, is separated from the Lowville horizon by a thickness of 200 feet of limestone with an Upper Chazy fauna.[14] The unconformity between the Theresa and Pamelia formations in the New York section is represented at Chambersburg by a 2,600 feet thickness of limestones, 2,000 feet of Beekmantown, and 600 feet of lower and middle Stones River age.[15] It should be stated also that the lower and middle divisions of the Stones River formation are regarded as essentially equivalent to lower and middle Chazy in time, but that the comparatively small Chazy basin was at this time entirely separated from the much larger sea to the south and west in which the Stones River deposits were laid down. "Finally the upper Stones River or Pamelia is only partially represented

[13] Letter of November 19, 1907.

[14] Winchell and Ulrich: Geological Survey of Minnesota, vol. iii, pt. 2, p. xc. Ulrich and Schuchert: Bulletin no. 82, New York State Museum, p. 641.

[15] Letter of November 19, 1907. Ulrich's more extended studies, as contained in his letter of March 25, 1908, lead him to regard this break as of even greater magnitude, the Theresa not representing the summit of the underlying formation.

in the Chazy section by the dove reef limestone at the base of the upper Chazy."[18]

Comparison with the Champlain and Mohawk Sections

Champlain valley.	Mohawk valley.	Watertown district.
Black River and Lowville, 40 to 60 feet.	Black River, 0 to 15 feet. Lowville, 0 to 25 feet.	Black River, 20 feet. Lowville, 60 to 75 feet.
Chazy: Upper, 200 feet........	Absent................	Absent.
Chazy:	....	Pamelia, 40 to 140 feet.
Chazy: Middle, 350 feet........	Absent................	Absent.
Chazy: Lower, 340 "	Absent................	Absent.
Beekmantown: Division E, 470 feet. Division D, 375 " . Division C, 350 " . Division B, 295 " .	Absent................	Absent.
		Unconformity.
Beekmantown, A, 310 feet. Passage beds, 30 to 75 "	Little Falls dolomite, 500 (?) feet.	Theresa, 20 to 60 feet.
Potsdam......................	Absent................	Potsdam.

The above correlation table is a modification of a more extensive table sent me by Ulrich as representing his views. We are in agreement in everything excepting perhaps the age of the Little Falls dolomite of the Mohawk valley, which is tabulated in accordance with my view instead of his. The determination of the age of the Pamelia formation and the recognition of the unconformity in the Champlain-Beekmantown are wholly Ulrich's.

In the Champlain valley sedimentation was in bulk and was comparatively uninterrupted during the Upper Cambric and Lower Siluric, except for the unconformity previously noted, and the deposits shown there today were laid down somewhat more removed from the margin of the subsiding basin than was the case in the Mohawk and Watertown districts, where the deposits were marginal, hence thin and more interrupted by breaks produced by oscillations of level. With the oncoming of Black River deposition we find for the first time evidence of connecting seas on all four sides of the Adirondack region, thus initiating the great depression of the succeeding Trenton and Utica epochs, when New York

[18] Ulrich: Letter of March 25, 1908.

State was nearly or entirely submerged for the only time in its geolo history, the early pre-Cambrian possibly excepted. The Lowville li stone, while typically developed on the south and west sides of the regi is but thinly developed in the Champlain valley, and is not sharply limited from the formations above and below, as in the Mohawk Black River valleys.

In the Watertown district the full thickness of the Lowville is sho with a closely related formation (the Pamelia limestone) beneath. Th shows considerable thickness only within the Clayton and Theresa qu rangles, and rapidly thins eastward, owing to overlap; so that in upper Black River valley only a thin edge of it is exposed and the ov lying Lowville practically rests on the pre-Cambrian rocks, not only Pamelia but also the Potsdam and Beekmantown being absent. T Pamelia has entirely disappeared by the time the upper Mohawk regi is reached, and there the Lowville rests unconformably on the somewh eroded surface of the Little Falls dolomite, the local name applied to supposed Beekmantown of the Mohawk valley. The Lowville here much thinner than in the Black River valley, and both it and the ov lying Black River limestone are thin and patchy in distribution thro the entire length of the valley, owing firstly to unevenness of floor which they were deposited, and secondly to their representing the extr northerly edge of their basin of deposit with little subsidence and s local oscillation prevailing along the shore.[17]

The Chazy deposits of the Champlain region were deposited in restricted Chazy basin, as named by Ulrich and Schuchert, and dur most of this period the Mohawk and Black River regions were o water, as was apparently the larger part of the state; but during latter part of Chazy time this land area underwent depression, wh crept in on the district from the south and west and finally reached Black River district, as shown by the Pamelia limestone there. T formation is older, but not greatly older than the overlying Lowville. its basin of deposit was separated from the Chazy basin by a land bar of considerable size, of which the whole Mohawk Valley region form part, the northerly edge of the Stones River migration on that mer being buried beneath younger rocks somewhere in southern New Yo northern Pennsylvania. The advancing Pamelia shoreline must had a trend of about north-northwest in northwestern New York, a already been shown. The Pamelia represents a formation deposit Chazy time, but in a wholly separate basin. According to Ulrich, was but scanty deposition in the Chazy basin during Pamelia time.

[17] Bulletin no. 95, New York State Museum, pp. 390-391.

ls in the case of the Chazy, much of the Beekmantown formation is ıfined to the Chazy basin and its southward extension, and did not ch westward into the Mohawk and Black River districts; so that ough this time also there was land extension in both these directions. e Beekmantown basin did, however, extend up the Saint Lawrence ley for a distance, though it never reached the Theresa district. Until Beekmantown of the Saint Lawrence valley receives more detailed dy, a definite comparison of it with the Champlain-Beekmantown is possible. It is clear that it thins westward to complete disappear-e and that the entire formation is not represented. The writer has n over the ground, but the work was of hurried character and done lve years ago, and the drift cover is so heavy that outcrops are few. is decidedly of the opinion, however, that it is the base which disap-rs westward instead of the summit. Such sections as that down the quette from Potsdam to below Norwood show Potsdam sandstone fol-ed by the passage beds of the Theresa formation, above which quite siliferous limestones come in after a very short vertical interval. The na has never been studied, but it is certainly much more like the ıer abundant fauna of the upper divisions of the Beekmantown than that of Division C. This means that uplift took place after the de-it of the Theresa formation, and that the break in the Champlain ey between Divisions A and B is the same break as that in the Theresa rict between Theresa and Pamelia formations, though of much less gnitude; hence that the uplift involved both the Saint Lawrence and ımplain valleys, and that the renewed depression which inaugurated Beekmantown was at first confined to the Champlain trough and its thward extension, and later sent a bay up the Saint Lawrence trough h progressive encroachment westward. The unconformity in the ımplain valley is of less magnitude than that about Theresa by at t 2,200 feet thickness of Beekmantown and lower and middle Chazy ts which are present in the one and absent in the other district. It is e noted that this reexpanded Beekmantown basin had somewhat dif-nt outlines from its upper Cambrian predecessor, probably not reach-the Theresa region at all, while in Canada the Beekmantown overlaps Potsdam onto the pre-Cambrian. The Chazy sea also had a bay in direction whose extent is unknown, but which in Canada overlapped Potsdam and Beekmantown onto the pre-Cambrian. Grabau argues the basal sandstones of these sections are of Beekmantown and Chazy instead of being Potsdam, this view being based on the supposed con-ıity of the section.[18] While it is quite possible that there may be

Bull. Geol. Soc. Am., vol. 17, pp. 584-585.

basal Beekmantown and Chazy sandstones in the sections, it is also likely that in many places the Potsdam is also present, and that the unconformity can be recognized there as in New York. Grabau also urges that the Beekmantown of these Canadian areas represents only the upper part of the formation as it exists in the Champlain valley, which view is precisely that urged here for the Beekmantown on the New York side.

In the correlation table on a previous page the Little Falls dolomite (the local name for the representative of the supposed Beekmantown of the Mohawk valley) is given as the equivalent of Division A of the Champlain valley and of the Theresa formation of the Watertown region. It should be frankly stated at the outset that this is the element in the table whose precise position and relationship is quite uncertain. This is owing in part to its unfossiliferous character and in part to the fact that the formation is separated by gaps from the other districts, so that it can not be directly traced from one to the other. In a recent publication the writer has argued that at least all the upper fossiliferous Beekmantown (Divisions D and E) of the Champlain valley is absent along the Mohawk.[19] Ulrich's discovery of the unconformity between Divisions A and B in the Champlain valley, necessitating the separation of Division A from the Beekmantown formation, at once raises the question as to whether the entire Little Falls dolomite may not lie below the horizon of the unconformity and hence not be Beekmantown at all, but be properly correlated with Division A and the Theresa formation and possibly even with the Potsdam. This was at first Ulrich's view, and still seems to the writer the one most in accord with the evidence as it can be gleaned from the New York sections, and hence it is the one adopted in the correlation table, though with open admission that the evidence is far from conclusive. Ulrich's later and more refined studies have led him to prefer a somewhat different view, though he does not regard any of the formation as of Beekmantown age.[20]

There is a second doubtful matter connected with the Little Falls dolomite, namely, whether or not it is a single formation. Vanuxem carefully distinguished the upper portion of the formation, the so-called "fucoidal layers," from the remainder, and he has been followed in this by most other observers in the district.[21] In the main the few fossils found in the formation have come from these fucoidal layers. According

[19] Bulletin no. 95, New York State Museum, pp. 389-390.

[20] While Ulrich's present views are of the greatest interest, they are based on the study of a mass of unpublished material, which renders it impossible to discuss them here. It is greatly to be hoped that his results may be published in the near future.

[21] Vanuxem: Geology of the Third District, pp. 30-37.
Darton: 13th Annual Report State Geology, pp. 417-422.
Cumings: Bulletin no. 34, New York State Museum, pp. 434-435, 441-442.

to Cumings, they have a thickness of 250 feet at Cranes village, two miles below Amsterdam and about 37 miles down the river from Little Falls. At Little Falls their thickness is only a few feet, so that they apparently thin rapidly westward. At the type locality of the Little Falls dolomite, therefore, these layers barely appear, while down the river they attain considerable thickness. At several localities *Lingulella acuminata* and *Ophileta complanata* are reported from the formation, and Cumings reports in addition two species of undetermined lamellibranchs. Hall figures a few other forms in volume 1 of the Paleontology. This fauna seems to the writer to indicate a probable equivalence of these fucoidal layers with the Theresa formation and Division A, or at least that they are no older. If this be correct, then either the bulk of the Little Falls dolomite is of substantially the same age or else there is an undiscovered unconformity between it and the "fucoidal layers." Until search has been made for evidence of such a break and until the fauna of the fucoidal layers is better known, the precise age of this formation must remain uncertain.

Conclusion

It has been shown that four formations—the Lowville, Pamelia, Theresa, and Potsdam—are present underneath the Black River limestone in the Watertown region, and that there is a great unconformity, both by erosion and by overlap, between the Theresa and Pamelia formations. The Pamelia formation is of upper Stones River age, and thus a formation hitherto unrecognized in the New York section. It is thought that the unconformity mentioned can be traced down the Saint Lawrence valley to the Champlain meridian and represents the expanded western representative of the break discovered by Ulrich in the Champlain valley between Divisions A and B of the Beekmantown. It is also thought that it represents the proper line of division for northern New York between the Cambrian and Lower Silurian systems, thus relegating to the Cambrian nearly 400 feet of strata which have hitherto been classed as Beekmantown. As thus restricted, the New York Beekmantown had much the same distribution as the succeeding Chazy, being laid down in an eastern basin, from which an arm projected westward up the Saint Lawrence trough, while the remainder of the state was mostly or entirely above sealevel.

The writer has recently discussed the early Paleozoic oscillations of level in northern New York, as indicated by the evidence in hand at the

time the reports were written.[22] The work was done and the first of the two reports transmitted for publication before the very important paper of Ulrich and Schuchert on "Paleozoic seas and barriers in eastern North America" came to hand.[23] In this paper the same matters were dealt with as details of a much larger theme. The observations set forth in the present paper necessitate slight modifications in these previously expressed views. The extent and importance of the unconformity which is here held to mark the proper line of division between the Cambrian and Lower Silurian systems indicates uplift of the entire region at the close of the Cambrian, with the succeeding Beekmantown depression limited to the Chazy basin. The invasion of the western part of the state by the Stones River waters must be made somewhat earlier than had been thought to be the case, and during Pamelia deposition a land barrier existed between these western waters and those of the Chazy basin. Ulrich has a mass of evidence of other oscillations and correlations, all of which he has most generously placed at my disposal; but the evidence comes from without the state, is unfamiliar to me, and as it is not essential to the present paper, which is concerned with the positive results of the New York work, it is not touched upon, since it is greatly to be hoped that he will himself be able to publish it in the near future.

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[22] Bulletin no. 77, New York State Museum, pp. 51-65, and Bulletin no. 95, pp. 386-394.

[23] Bulletin no. 52, New York State Museum, pp. 633-644.

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TOPAZ-BEARING RHYOLITE OF THE THOMAS RANGE, UTAH[1]

BY HORACE B. PATTON

(Read before the Society December 31, 1907)

CONTENTS

INTRODUCTORY

For the past twenty or twenty-five years the colorless transparent topaz crystals from the Thomas range of Utah, with their many crystal faces and wonderfully brilliant luster, have been very familiar objects with all mineral collectors. Although this interesting occurrence has been briefly described by several writers and the crystals have been accurately measured and figured,[2] but little information of a detailed nature has been

[1] Manuscript received by the Secretary of the Society March 17, 1908.

[2] Alling: "On the topaz from the Thomas range, Utah." American Journal of Science, vol. 33, 1887, p. 146.

furnished as to the actual environment and as to the conditions under which they were formed. An opportunity to study the crystals and the rocks in which they occur was afforded the writer by a visit to the locality during the early part of last summer, and the observations made at that time and a more leisurely study made of the large amount of material collected furnish the excuse for this paper.

The discovery of this topaz locality was first made by Henry Engelmann, geologist of an expedition across the Great basin of Utah conducted by Captain J. H. Simpson in the year 1859.[3]

This discovery of Engelmann appears to have been forgotten or overlooked, probably because of his rather vague description of the locality. In 1884, however, the same locality was visited by Professor J. E. Clayton, of Salt Lake City, and numerous specimens collected. Since that time many others have journeyed to the place for the purpose of collecting the crystals.

In 1886 Whitman Cross published a very brief description of the topaz crystals of the Thomas range and of the rock in which they occur. Mr Cross, however, did not visit the locality, but was indebted for the scant material at his service and for information concerning it to the kindness of Professor Clayton. His description is quite accurate, so far as his information went, and is given in connection with a fuller description of a very similar occurrence at Nathrop, Colorado, in a paper entitled "On the occurrence of topaz and garnet in lithophyses of rhyolite."[4]

A further very brief description of this occurrence has been furnished by Arthur J. Jones, who visited the place in 1891.[5]

Further brief mention of these topazes, aside from the communication by A. N. Alling, as given above, are made by G. F. Kuntz[6] and by O. C. Farrington,[7] who gives an excellent colored illustration of the wine-colored crystals clustered in a lithophysal cavity.

Location

The exact locality in which these topaz crystals are found is in one of the desert ranges of Utah designated by Clayton the Thomas range and

[3] Report of explorations across the Great basin of the Territory of Utah, etcetera, by Captain J. H. Simpson, Engineer Department, U. S. Army. Washington, 1876, p. 324.

[4] American Journal of Science, vol. 31, 1886, p. 432.

[5] Topaz crystals of Thomas mountain, Utah. Proceedings of the Iowa Academy of Science, vol. 2, pp. 175-177.

[6] U. S. Geological Survey, mineral resources, 1883-1884, p. 738; U. S. Geological Survey, mineral resources, 1892, p. 764. Gems and precious stones, p. 67. New York, 1892.

[7] Gems and gem minerals, p. 121. Chicago, 1903.

located about 40 miles north of Sevier lake and a little more than that distance northwest of the town of Deseret. The name Thomas range is not, however, familiar to residents of Deseret and vicinity, who refer to it as the Dugway range and who speak of the topaz locality proper as Topaz mountain. As will appear later, the crystals of topaz are not limited to a definite portion of the range, but are found scattered throughout a rhyolite formation that extends many miles to the north and west; but as the crystals are extraordinarily abundant at this particular place, it will be convenient to refer to the locality as "Topaz mountain."

On the most direct road from Deseret to Topaz mountain one passes through a small range locally known as the Drum mountains, which are composed—as far as visible from the road—of blue limestone and quartzite, with flows of basalt and rhyolite and probably also of andesite. Several small mines and prospects with copper and gold ores have been worked here in the past and were under active investigation at the time the writer visited the region.

In these so-called Drum mountains, and close to the above mentioned mines, is located the postoffice called Joy, in Juab county. Eight miles northwest of Joy, and also in Juab county, is the Topaz mountain.

Description of Topaz Mountain

On the east side the range, of which Topaz mountain is a part, stands up very conspicuously, like a sharp ridge, and may be seen for many miles. Its color is a very light gray or almost white compared with the dark brown to reddish colored hills that are seen to skirt the ridge on the north and south and that run out some 2 miles to the eastward and form foothills to the main mountain mass. As a matter of fact, however, except for a spur some half mile in length that runs out southeasterly from the main crest and nearly at right angles thereto, the mountain mass does not form a ridge, but is rather a greatly dissected tableland that rises very precipitously on the southeastern face for a distance of some 4 or 5 miles to an estimated height of 1,000 or perhaps 1,200 feet above the base, but that to the westward and northwestward stretches out apparently indefinitely.

The rocks that form this part of the Thomas range are volcanic in origin and lie upon a level or more or less rolling platform of sedimentaries of age unknown to the writer, but quite possibly Carboniferous. The only sedimentary rock actually seen, except some of volcanic origin, was a bluish gray limestone that lies horizontal in the nearly level stretches southeast of the range. On this limestone lies a buff-colored rhyolitic

tuff of varying thickness, and on this in turn a succession of lava flows, beginning with andesitic types, or perhaps locally with andesitic breccias, and ending with the more acid rhyolites. At the base of these rhyolite flows is to be seen, locally developed, a thin flow of obsidian that may be quite free from crystals or crystallization products or that may locally develop small solid spherulites.

The rocks that form the outlying foothills on the east and southeast and that are referred to above as having a dark brown or red color are mostly andesitic in type, but the color of the surface is usually much darker than that of the freshly broken rock and is no safe indication of the basidity of the rock. In fact, many of the rhyolites of the region are remarkably dark colored on the weathered surface.

The later rhyolite flows undoubtedly make up the bulk of the volcanic rocks, but it is not easy to distinguish sharply between the flows, nor to trace their lines of contact, nor to measure their thickness, especially in case of the rhyolites. It would require more time than was at the disposal of the writer and a study of more distant parts of the range to settle these matters with certainty. It would seem, however, that in the immediate vicinity of Topaz mountain there are four and perhaps five lava flows. The latest of these flows is the one that more immediately concerns us, in that it contains most of the topaz crystals.

The Topaz-bearing Rhyolite

This rhyolite is several hundred feet thick and forms the crest of the range on the southeast face. It varies in color from nearly white to light brown or brownish gray. It is a lithoidal rhyolite, never showing a trace of glass. In places it appears massive and structureless, but at other places flow structure is very pronounced, so as to cause the rock on weathering to split into thin slabs. The flow planes stand at all angles, being fully as apt to be vertical as horizontal, and in many places are greatly folded and contorted. The rock is apparently not porphyritic, although it may be seen upon close observation to contain numerous very small crystals of quartz and of sanidine. Dark colored minerals are entirely wanting. This absence of ferromagnesian minerals may often be accounted for in such rocks by supposing that they have been removed by percolating waters which leave the rock more or less rotted. In fact, the rhyolite does appear to be more or less kaolinized when examined in the hand specimen alone. Under the microscope, however, the feldspars present a surprisingly fresh appearance and very little kaolin-like material is disclosed.

FIGURE 1.—LITHOPHYSÆ IN RHYOLITE, THOMAS RANGE, UTAH

Natural size

FIGURE 2.—FRAGMENT OF RHYOLITE SHOWING CAVERNOUS STRUCTURE, THOMAS RANGE, UTAH

Structure produced by exposure to desert winds. 1/2 natural size

STRUCTURE OF UTAH RHYOLITE

Solid spherulites were nowhere observed, but the delicate hollow lithophysæ are developed in great perfection and beauty. Their distribution is very irregular. As a general thing, they are not abundant. In fact, many portions of the flow are entirely free from them. This is especially true where flow structure is very pronounced and the rock splits up under the influence of the weather into slabs and where the rhyolite presents a dense and more strictly cryptocrystalline texture. Lithophysæ are also not so apt to occur in the darker colored portions of the rhyolite. In other places, especially where the rhyolite is very light colored and the texture more evidently crystalline, lithophysæ may occur in great abundance—indeed, they may crowd thick upon each other. Flow structure is not altogether absent in those portions of the rhyolite where lithophysæ abound, but it is not very noticeable and may be seen chiefly in the fact that the lithophysal cavities are often flattish and strung along in more or less definite lines parallel to the direction of flattening. The coalescing of such flattened cavities so as to form larger flat openings is also noticeable, but the solid rock between the lithophysæ shows even under the microscope but scant traces of a true flow structure.

On the natural weathered surface of the rock the lithophysæ are rarely well preserved, but develop into more or less irregular cavities, yet when freshly quarried they are often of extreme delicacy and beauty, being composed of multitudes of concentric, crystal-lined shells separated from each other by equally narrow spaces. They are built up almost entirely of quartz crystals with a very little sanidine and are nearly white in color (see plate 12, figure 1). The quartz crystals are clearly seen to line both sides of each shell and are large enough to be readily recognized by means of a magnifying lens or even with the naked eye. They vary in size from one millimeter downward. The forms are the customary prism and positive and negative rhombohedron, resembling a simple pyramid. No tridymite was observed.

These lithophysæ in some respects strongly resemble and are still more beautiful than those of the now classic locality in the Yellowstone National Park, Obsidian cliff, which have been described with great fullness and clearness by Iddings.[8] They differ from these Obsidian Cliff lithophysæ in the greater size of the quartz crystals that line the delicate, petal-like shells, in the character of the accompanying minerals, and in the nature of the enveloping rock.

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[8] U. S. Geological Survey, 7th Annual Report, pp. 265-200; U. S. Geological Survey, Monograph 32, pt. 2, 1899, p. 416; U. S. Geological Survey, Bulletin no. 150, pp. 153-159.

The rock immediately adjacent to the lithophysæ may be designated as a lithoidal rhyolite, in that it is crystalline rather than glassy and has a stony luster. It is entirely free, however, from the branching rod-like feldspar aggregates and from the microspherulitic growths so characteristic of the Obsidian Cliff occurrence, and never presents a porcelain-like appearance, although in some places, where lithophysæ are absent and flow structure is unusually pronounced, the rhyolite has a fairly smooth fracture, owing to fineness of grain, approximating that of the porcelain-like lithoidite of Obsidian cliff. On the contrary, this rock is very distinctly holocrystalline and has a very rough fracture. The small quartz phenocrysts, 1 to 2 millimeters in diameter, have a smoky color, in marked contrast to the clear white of the quartz crystals that line the shells.

Under the microscope may be seen in thin-section a few small phenocrysts of sanidine and of quartz, all in roundish grains. Biotite and other ferromagnesian minerals are entirely missing. The groundmass consists of fairly coarse but very irregular and even ragged edged individuals of sanidine and of quartz, the former apparently predominating. There is a certain amount of grayish, dirty looking impalpable powder that probably represents some alteration product, possibly kaolin. The character of this groundmass, taken in connection with the groundmass of other portions of the extensive rhyolite flow more remote from the lithophysæ, impresses the observer as indicating a devitrification product of an originally glassy rock.

In addition to the customary constituents of a rhyolite, this rock also contains the mineral topaz, not merely in the cavities, but as an important ingredient of the rockmass. A description of this topaz follows in these pages under the heading "Rough opaque topaz."

Weathering Features

The effect of the desert climate on this rhyolite is very remarkable. In the first place, very little soil and almost no vegetation is to be seen, except in places where the prevailing winds tend to accumulate soil. As a general thing, the rock is swept absolutely bare. Under the influence of the climatic conditions, the rock does not rot, but disintegrates into sand that is blown away by the wind as fast as liberated. Naturally the first parts to be thus attacked are the delicate walls of the lithophysæ, or, in case these are not present, little cavities are scooped out where soft or more friable parts of the rock occur. Thus the rock surface becomes

pitted with sharp depressions or excavations of all sizes. On the bottom of such large and small cavities it is not uncommon to find topaz crystals lying. Not infrequently such crystals lie imbedded in a layer of sand and may then have preserved their original wine color. Both colorless and opaque crystals were found in such cavities.

Further exposure to the weather causes the cavities to deepen and enlarge and the rock becomes honeycombed. The enlarging cavities unite by the wearing away of thin intervening partitions until they become miniature caverns perhaps 6 or 8 feet across and separated by the thinnest of walls. Eventually the steep mountain side presents the most rugged and ragged appearance imaginable and is suggestive of a great porous sponge. Unfortunately photographs of these rugged formations were ruined, but a fair notion may be obtained from examining a small piece of the rock. It is only necessary to imagine a mountain side composed of this same material with all the details on a greatly enlarged scale. Figure 2 of plate 12 is from a photograph of such weathered rock fragment.

Minerals occurring in the Cavities of the Rhyolite

GENERAL REFERENCE TO THE MINERALS

As already mentioned, the occurrence of topaz crystals in the rhyolite of the Thomas range has long been known and their mode of occurrence has been briefly described. In addition to the topaz crystals, there are a few other minerals that likewise occur in these cavities and that will receive brief description later. These are specular hematite, garnet, and bixbyite.

TOPAZ

Physical characteristics.—Heretofore the only topazes that have been described as coming from the Thomas range have been the transparent and usually colorless variety; but there are other topaz crystals that I shall designate as opaque topazes that are of perhaps equal if not greater interest to the petrographer. These latter are usually rather rough in their crystal development; but there was found in one locality a smooth and sharply crystallized variety of this opaque topaz that occurs under sufficiently different conditions to justify a separate description. The topazes of this region will be described, therefore, under the following three heads: Transparent topaz, rough opaque topaz, and smooth opaque topaz.

Transparent topaz.—These are the crystals that are already well known to mineral collectors and that occur invariably in small cavities of the rhyolite. As already mentioned by A. H. Jones,[9] the topaz crystals of this locality are all originally of a wine color, which color fades on exposure to the sunlight. It invariably happens, therefore, that all the crystals found on the surface are perfectly colorless and all have a wine color when found in a freshly opened cavity. This wine color has a characteristic brownish tint and is very beautiful in its deeper shades. The depth of color varies considerably, but is always pronounced. The larger crystals have naturally a deeper shade, owing to their greater thickness; but, aside from the thickness of the crystal, some are darker than others. It is unfortunate that the color, as is so often the case with topaz, is not permanent. The color disappears quickly with very gentle heating. After exposure to bright sunlight for thirty hours a marked fading of the color was to be noticed. After forty-eight hours' exposure to direct sunlight the smaller and lighter colored crystals lose their color, and after about seventy hours the deeper colored ones become nearly colorless (see plate 13, figure 1).

It occasionally happens that one finds a crystal or cluster of crystals lying partly buried beneath the surface and partly exposed, so that the buried part is wine colored and the exposed portion perfectly colorless.

These crystals are mostly small, say one-quarter to one-half inch, occasionally one inch in length. In breadth they average about one-half the length, although at times they are much more slender than this. Undoubtedly larger crystals do occur, and when the locality was first visited must have been found on the surface, but naturally the larger ones are the first to be picked up.

There is no doubt that these topaz crystals were formed after the lithophysæ were practically complete, as they grow upon the walls of the cavities and inclose to a considerable extent the quartz material of these walls. The crystals are attached sometimes at one end only, sometimes along the whole side, and again both ends may be attached, while the center is free and clear. Doubly terminated crystals are not altogether rare, but they are not often found free on the surface of the ground. Once in a while it happens that a crystal is attached to the very thin wall separating two adjacent lithophysæ and grows freely into each cavity, thus producing double terminations. Clusters of crystals produced by the growing of one crystal upon another are by no means uncommon.

The habit and crystal forms of these topazes are already well known

[9] Loc. cit., p. 176.

FIGURE 1.—TOPAZ CRYSTALS IN A LITHOPHYSAL CAVITY, THOMAS RANGE, UTAH

5/4 natural size

FIGURE 2.—OPAQUE TOPAZ CRYSTALS, THOMAS RANGE, UTAH

The upper left hand cluster are "rough," the others "smooth." 4/5 natural size

TOPAZ CRYSTALS FROM UTAH

and need not be here described at length. Mr A. N. Alling, in the paper above quoted, mentions the following forms:

Brachy pinacoid (010), basal pinacoid (001), two prisms (110) and (120), two brachy domes (021) and (041), and four pyramids (223), (111), (221), and (441).

There are other forms not as yet determined that would repay a careful study, but it is not within the scope of this paper to dwell upon the crystallographic relationships.

The brilliant luster of these topazes has often been commented on, and this brilliancy holds for the crystals that have long been exposed to the weather as well as to those freshly quarried. It would seem as though they are practically unaffected by ordinary weathering influences.

Rough opaque topaz.—The topaz crystals of this region are not confined to the lithophysal cavities, but also abound in the solid rock. In this case they are not transparent, but relatively opaque and of a grayish color. In form they are rather slender, being from three to five times as long as wide. They are also considerably larger than are the colorless crystals of the cavities. They are seldom much less than an inch in length, and from this they vary up to two and one-half inches or more. The ends are almost invariably rough or even ragged in appearance, as though they had been subjected to the action of some solvent. Usually, however, one can see a trace and very often much more than a trace of one or more terminal forms. The pyramid (221) is the one usually in evidence in such cases and other forms subordinate to this. The prism faces, on the other hand, are invariably present and well developed, but are somewhat roughened by clinging quartz crystals. The unit prism (110) is invariably very conspicuous, while the other prism (120) is present only as two very narrow and inconspicuous strips along the sharper prism edge. The interior of these opaque crystals is crowded with quartz grains, as disclosed under the miscroscope in a thin-section. These are not the very irregular and ragged-edged quartz individuals that characterize the groundmass of the rhyolite, but are sharply defined roundish grains, with a marked tendency to definite crystal forms, and occasionally they are perfectly formed crystals with the prism and plus and minus rhombohedron. In the one crystal investigated the quartz inclosures make up perhaps one-sixth of the entire bulk. They average about 0.05 millimeter in diameter, with extremes of 0.1 millimeter and 0.02 millimeter. Larger quartz crystals may be seen adhering to the outside; also thin leaflets of specular hematite. Apparently none of the feldspar that makes up a large proportion of the groundmass of the surrounding rhyolite is to be found within these topaz crystals.

These opaque topaz crystals are not always nor usually single individuals, but clusters of two to many crystals grown together. In these clusters one individual shaft is usually larger than the others that branch out from it in different directions (see plate 13, figure 2).

There are numerous transitions between these opaque crystals and the transparent ones. This is due to the fact that an opaque crystal may not be confined to the solid rhyolite, but may project into a free cavity. In this case the projecting portion, usually an end, will have the customary terminations of the other crystals in the cavities and will likewise be transparent and of a wine color. As a matter of fact, the opaque crystals when taken out from a freshly broken rock are not of a gray color, but are of a mingled gray and wine color. From the foregoing it would appear that the two varieties are due simply to different conditions of growth.

Smooth opaque topaz.—These crystals are exactly analogous to the last described variety, in that they have the same habit and about the same color and in that they occur imbedded in a solid rock. As crystals, the chief distinction lies in the extreme smoothness of the faces and in the fact that they have usually perfect terminations on both ends. Single crystals are very rare. Rather they occur in clusters similar to those just described for the rough opaque variety, with many prongs branching out from a heavier central shaft. Only a very few perfect crystals and clusters were found, as, on account of the brittleness and the easy basal cleavage, the prongs are extremely liable to be broken off. In one case as many as twenty subsidiary prongs were counted on one cluster. The forms are the same as those described for the rough opaque variety, namely, the two prisms with the same relative sizes and the pyramid (221). In this case, however, other forms, with faces barely visible upon close observation, can be more readily made out. For instance, a second pyramid and all three pinacoids. The orthopinacoid that may thus be made out is a form that has not as yet been described from this locality.

Another important distinction is the nature of the rock in which these smooth crystals are implanted. They were found in just two points about 50 feet distant from each other, and in each case they were developed in a fragment of rhyolite tuff that had been caught up by the rhyolitic lava stream. The tuff is quite firm, very fine grained, perfectly uniform in texture, and of a gray color. The crystals have been freed by the disintegration of the tuff and were found lying on the surface or inclosed in the soil immediately below the fragment of tuff or embedded in a fine

gray sand that lay in the bottom of a cavity of one of the tuff masses and that resulted from the slow disintegration of the same. Nearly all the perfect crystals were found in this last named place. Those in the soil nearly always had some or most of the prongs broken off. It was impossible to break a crystal uninjured from the solid tuff.

Under the microscope a thin-section of this tuff disclosed an aggregate of very irregular grains of quartz and of sanidine that vary in size from 0.1 millimeter downward. The rock is quite similar in mineral composition to the rhyolite in which it is embedded, but quite different in appearance, both in the hand specimen and in thin-section. Thin-sections cut through one of these crystals parallel to the basal pinacoid and to the macropinacoid show a perfectly normal crystal of topaz inclosing countless minute and invariably sharply defined crystals of quartz that together make up something like one-quarter of the bulk. These crystals measure from 0.03 millimeter to 0.005 millimeter. They contain minutest dust-like particles that are apparently exactly like dusty particles in the tuff. These particles are sometimes black and opaque, sometimes reddish or brownish, and are more sharply defined in the topaz crystals than in the rock. No other inclosures than the quartz crystals occur in the topaz.

The following chemical analyses of the rhyolite tuff in which the smooth opaque topaz crystals occur and of one of the smooth opaque topaz crystals were carried out in the chemical laboratories of the Colorado School of Mines. The analysis of the tuff was made by J. W. Whitehurst and that of the topaz crystal by J. H. East, both students of the class of 1910. In case of the rhyolite tuff, it is readily seen from the analysis that the tuff does not differ materially from a normal rhyolite. The topaz analysis shows naturally an abnormally high percentage of silica, due to the inclosed quartz crystals. A calculation based on this excess of silica indicated that 18.78 per cent of the material of this opaque topaz is inclosed quartz.

Rhyolite Tuff		*Smooth opaque Topaz*	
SiO_2	74.50	SiO_2	44.68
Al_2O_3	13.28	Al_2O_3	44.84
Fe_2O_3	1.50	Na_2O	trace
CaO	1.46	K_2O	trace
MgO	trace	H_2O	trace
K_2O	3.54	F	13.44
Na_2O	5.23		
Total	99.51	Total	102.96

It would seem very clear from a study of these smooth opaque topazes as well as of the rougher variety that the period of quartz crystallization was practically identical in time, or nearly so, with that of topaz formation. The vapors or solutions, or both, that were responsible for the development of topaz in the cavities were also responsible for the development of the same mineral in the solid rock. In the latter case room had to be made for the crystal, which was partly accomplished by the complete removal of the feldspar and by the recrystallization of the silica into definite quartz crystals. In describing an occurrence of topaz and garnet in lithophysæ in a rhyolite at Nathrop, Colorado, Mr Whitman Cross says:

"The mode of formation of the topaz and garnet is not fully determinable, but it is evident that they are not secondary products, like zeolites, but primary, and produced by sublimation or crystallization from presumably heated solutions, contemporaneous or nearly so with the final consolidation of the rock."[10]

If this is true of the topaz crystals found in the lithophysal cavities—and to the writer this seems to be indisputable—then it must also be true of the other topaz crystals scattered throughout the mass of the rhyolite. This would make these opaque topazes not exactly foreign matter, but an integral part of the rock.

In the formation of both the rough and smooth opaque topaz crystals the material of which the inclosing rock was composed necessarily formed a serious hindrance to the growth of the crystal. In the case of the tuff, the crystals must have been formed in the solid rock under the influence of the hot lava and by means of the same vapors and solutions that caused the development of the crystals in the rhyolite, and in their formation they must have made place for themselves through the removal of the rock ingredients by solution or by partial recrystallization. Where the constituents of the rock were very fine and uniform, as in the case of the tuff, they offered less resistance to the recrystallizing agencies, with the result that the topaz crystals were able to assume perfect forms.

In this connection it may be noted that the tendency to the development of the two prism forms, especially of the unit prism, was much stronger than in the case of the other forms, so that these forms are always more or less in evidence, while the tendency to develop terminal forms was not strong enough to overcome the resistance in case of the coarser grained rhyolite, but was sufficient to overcome the weaker resist-

[10] American Journal of Science, vol. 31, 1886, p. 437.

ance of the very fine grained tuff. It may also be noted that of the four or more possible pyramids, as well as of the domes and basal pinacoid, the pyramid (221) was the only one capable of strong development, even under the most favorable conditions.

Distribution and frequency of the topaz crystals.—As already stated, the topaz crystals of the lithophysal cavities are very fluctuating in amount. Where the lithophysæ are characteristically developed the crystals are very abundant. This is more apt to be the case where the rock is of a very light gray or nearly white color. But true lithophysæ pass by insensible gradations into irregular cavities that show but little if any development of concentric shells. These cavities also may contain topaz crystals, but are not so apt to do so. In such portions of the rhyolite one will have to hunt carefully for the topazes; but it often happens that where the cavities are scarce or where they contain but few topaz crystals, the opaque crystals are very much in evidence. For instance, over limited areas of the exposed rhyolite one may see at times one opaque topaz crystal or cluster to every square foot of surface. At other times and places only an occasional crystal may be seen. In one particular instance the writer extracted from about four cubic feet of rotted or partially disintegrated rhyolite 336 crystals and clusters. These crystals were in many cases distinctly transparent or partially so, but many of them were transitional to the opaque variety. Most of them were of very fair size, being three-quarters of an inch to one and one-half inches in size. The total weight of these 336 crystals was 24 ounces. These crystals were undoubtedly in place. The opaque variety has probably a much wider distribution than has the transparent crystals. In a letter from Mr Maynard Bixby, of Salt Lake City, to whom the writer is indebted for many courtesies and for much valuable information as to this topaz locality, it is stated that these opaque topazes occur "all through the belt of rhyolite" and are well developed at a locality where the mineral bixbyite was first found, some 20 miles northerly from Topaz mountain.

SPECULAR HEMATITE

The occurrence of specular hematite, usually in the form of thin flakes, in cavities of rhyolite and of other acid igneous rocks is a very common feature in the Cordilleran west, but its occurrence in plainly developed lithophysæ has not, so far as the writer is aware, been noted heretofore. It is, however, very universally present in the lithophysæ of Topaz mountain, attached to the topaz and to the quartz crystals. Its

development must have been contemporaneous with that of the topaz, or at least with the later stages of the topaz development, as they may be noticed growing upon the topaz and partially or completely inclosed in its mass. They are usually very minute, one or two millimeters or even less, and then may be very numerous; rarely they attain to a diameter of half a centimeter. They are perfectly black, highly lustrous, and very thin and fragile. They occur not only in the lithophysal cavities, but are also abundant attached to the rough opaque topaz crystals embedded in the solid rhyolite.

GARNET

The occurrence of garnet at Nathrop, Colorado, in the cavities of rhyolite was described by Cross in the paper above quoted.[11] They were described as occurring in lithophysæ associated with topaz, and were found by analysis to be spessartite. The largest crystals found, according to Cross, measured 1 centimeter. It may be noted in passing that a specimen of the Nathrop garnet now in the collection of the Colorado School of Mines measures somewhat more than this, namely, 16 millimeters.

At the locality which I have designated as Topaz mountain only one very small garnet was observed, but at a point over the mountain to the westward, some three or four miles from the rather limited area over which topaz crystals are abundant, the writer was fortunate enough to find a few very beautiful garnets of unusual size. The rock is a lithoidal rhyolite with quite marked flow structure that weathers into thin slabs and that contains small irregular cavities. On the exposed surface the cavities did not appear to be lithophysæ; but, as already mentioned, weathering very often destroys on the exposed surface all trace of the lithophysal structure, and as no means were at hand to blast the rock, this point could not be determined. The garnets were scattered sparingly over a surface some hundred feet wide by two hundred feet long. Most of them were very rough, showing only a face or two, owing to the fact that the cavities were too small to accommodate them. The largest and best crystal measures one and one-half inches and has twelve trapezohedral faces entirely or partially developed. The rest of the crystal bears the rough imprint of walls of the cavity in which it grew. The luster is extremely brilliant and the color a very dark brown, beautifuly streaked with a light bronze brown. The crystal form is the usual trapezohedron (211) with the merest trace of a dodecahedron. The crystals are stri-

[11] American Journal of Science, vol. 31, 1886, p. 434.

ated parallel to the dodecahedral faces and the striæ run also parallel to the light brown streaks.

One garnet crystal was found that has a topaz grown into it in such a way as to show that the garnet had partially grown around the topaz. This indicates that the topaz had formed before the garnet was completed.

In this connection it may be noted that the writer, a week or so after leaving the Thomas range, ran across another occurrence of garnet in lithophysal cavities in rhyolite. This was in Lincoln county, Nevada, a few miles west of the Utah line and near the new gold camp called Gold Spring. This new camp is about 12 miles from the town of Modena, Utah. The rhyolite forms a dike that rises conspicuously a hundred feet or so above the heavily wooded hillside. The dark reddish brown garnets have the customary trapezohedral form and vary from one-quarter to three-quarters of an inch in diameter.

BIXBYITE

In a paper entitled "On bixbyite, a new mineral, and notes on the associated topaz," Penfield and Foote, in 1897,[12] described the mineral which they named bixbyite as an oxide of manganese and iron, $FeO.MnO_2$, and as occurring implanted on topaz crystals, and as having isometric forms, chiefly the cube. The bixbyite crystals are described as occurring with both transparent and opaque topaz; and, further identifying the opaque crystals of topaz with those described in this paper, the authors add:

> "The opaque crystals, as shown by microscopic examination, are not pseudomorphs, but consist of fresh unaltered topaz containing minute quartz crystals, which evidently have been included during crystallization."

As the writer was not aware of the fact that the new mineral, bixbyite, was likely to be found at Topaz mountain, no search was made for it and none was noted; but, on looking over the material collected, it has been found adhering to rough opaque topaz. There is every reason to believe, therefore, that it must also occur in the lithophysæ proper.

CONCLUSION

In conclusion it may be well to state that the notion that prevails in some quarters that the topaz crystals may be fairly scooped up on the

[12] American Journal of Science, 4th series, vol. iv, 1897, pp. 105-108.

Thomas range is very far from the truth. The crystals are abundant in only a comparatively limited area—say an area half a mile or less in each direction. Undoubtedly the crystals are present over this area in millions, but they are mostly very small, the larger ones having long since been picked up. They abound in the sand of the dry stream beds, and may be thus traced for miles. These minute crystals shine, too, just as brilliantly in the sunshine as do the larger ones, and if one endeavors to locate a good sized crystal by the brilliancy of its sparkle, he will find himself engaged in the unprofitable, not to say undignified, occupation of chasing up pinheads.

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OUTLINES OF HYDROLOGY[1]

BY W J MCGEE

(Read before the Society December 28, 1906)

CONTENTS

PROLOGUE

In general the progress of attention is in the direction of concentration, or from the remote to the near, from the rare to the common, from the exceptional to the usual, from the abnormal to the normal, and usually from the simple to the complex; and concomitantly the progress of consciously systemized knowledge has trended from sky to soil and from star

[1] Manuscript received by the Secretary of the Society August 10, 1908.
This paper was read under the title "River sediment as a factor in applied geology." It is revised to July 30, 1908.

to man, yielding an orderly series of sciences ranging from astronomy to anthropology. In the course of the progress two factors have prevailed: first (in significance rather than order), the ceaseless and ever-growing desire to know merely for the sake of knowing—that is, the spontaneous interadjustment of mentality with external nature; and, second (in importance, though often first in order), the conscious or unconscious habit of utilizing knowledge—that is, the endless interadjustment between man and external nature; and under the influence of these factors the sciences and the applications of science have come up concurrently, sometimes the one and again the other in the lead. Especially in the domain of the natural sciences, habit commonly precedes thought and the object-matter is used before the science is framed; so plants were utilized before phytology, animals before zoology, rocks and minerals before geology; so, too, descriptive aspects have generally arisen the earlier, as geography before geology and ethnography before ethnology; and in general the progress in systemization has responded to the demands for knowing and for applying jointly.

Now among the objects-matter of knowledge, none are more vital than water: It is in accord with its nearness to human interest that it was late to receive close attention, and that even yet it has received little thought save in the descriptive aspect of hydrography; yet the habit of utilizing and applying it, which arose unwittingly in the unwritten past, has spread so widely and become so large a part of modern life as to warrant concentrated and conscious consideration. Accordingly, in the light of the long course of the development of the sciences, in the light of the transcendent importance of the water of the earth to human welfare, and in the light of the inherent interest of the object-matter itself, it would seem clear that the time is ripe for establishing definitely the Science of Water, already known somewhat vaguely as hydrology.

The relations of hydrology with other sciences would naturally correspond with the relations existing among these others. It would derive method from the chiefly formal or subjective sciences (mathematics pertaining to quantities, astronomy pertaining to masses, chemistry pertaining to substances, and physics pertaining to forces, with their several subdivisions and ramifications); it would share object-matter with the chiefly natural or objective sciences (meteorology pertaining to air, geology pertaining to rocks, phytology pertaining to plants, zoology pertaining to animals, and anthropology pertaining to men, with their several and various subdivisions and combinations); and in some measure it would tend to unite the two groups. The relations would be particularly close with geology and meteorology, since water is at once a terrestrial

mineral and agency and a highly effective constituent of the atmosphere; at least at the outset, it would naturally form a branch of the former science, with its organized instrumentalities and institutions. In the general order of sciences running from the simple to the complex (astronomy based on gravity and other mass relations which may collectively be denoted molarity, chemistry based on affinity—or molecularity—plus molarity, phytology based chiefly on vitality plus affinity and molarity, zoology based largely on motility plus vitality and affinity and molarity, and anthropology based mainly on mentality plus all the simpler bases), hydrology would occupy an intermediate position, in some measure spanning the interval between the bases of affinity and vitality—this in ways which can only be suggested now and which must remain for research to elucidate and demonstrate.

Elements of Hydrology

WATER AS A PLANETARY CONSTITUENT

The mineral H_2O, forming the hydrosphere, takes a leading role in the play of terrestrial progress: Practically covering the planet, existing in the three states of solid and liquid and vapor under natural temperatures, extraordinarily high in molecular inertia or specific and latent heat, and constantly changing from one state to another with the diurnal and annual procession of planetary movement, it is the most effective known agent in determining external terrestrial conditions. Without it, the earth would be lifeless; with its quantity quadrupled, the globe would be uninhabitable by higher life-forms; perhaps decreasing slowly in amount and certainly concentrating in deepening seas, it has permitted the growth of continents and the evolution of organisms, now limits the habitability of the one by the other, and with continued diminution threatens organic existence in that the world's deserts are manifestly increasing, though under Chamberlin's planetesimal theory the aggregate volume may be so increasing as to balance the concentration. In its movements and changes of state the leading external agency of earth-making, it first brought forth and then gave form to the continents; and the organisms developed within it to reach higher estate on land depend on it both for the chief part of their substances and for all their vital processes. A growing and living world without water is unthinkable.

The temperature and climate of the globe are determined by an atmospheric mechanism of which the dominant factor is H_2O. The aqueous vapor in the atmosphere forms a blanket against radiation in which the sun heat is both conserved and distributed; when liquefied or solidified

by cooling the latent heat tempers the atmosphere and lithosphere, and when warmed it returns to vapor, and the latent heat again equalizes the temperature; and through this conservation and equalization of heat derived primarily from the sun, the range of temperature from equator to poles, from day to night, and from summer to winter is reduced to a third or a fifth of what it would be if dependent directly on insolation and radiation. Despite the diathermancy of the air, the atmosphere as a whole is so effective an agency for retaining sun heat that the temperature of the external earth is conditioned not (almost not at all) by the planet's proper heat, but by radiation from the distant luminary; and the chief heat-conserving constituent is water, mainly in the form of vapor, of which each particle, as shown by Tyndall, absorbs heat many thousand times more rapidly than a like particle of air. With an oceanless surface and a water-free atmosphere, the temperature of the earth would range so widely and fall so low as to render it uninhabitable by organized beings.

THE HYDROSPHERE AND ITS DIVISIONS

The volume of the hydrosphere is about 1/600 that of the entire geosphere. The dominant division of the terrestrial H_2O (some 310,000,000 cubic miles, or 1/840 of the volume of the solid earth) occupies depressions in the earth crust as seas. Probably next in volume is the division permeating earth and rocks as ground water; if 5 per cent of the ten-mile earth shell (Whitney finds the optimum soil moisture to range from 4 per cent to 20 per cent, which increases at ground-water depths to an average exceeding 15 per cent in humid regions, but runs lower in arid regions and generally at greater depths), it reaches some 100,000,000 cubic miles. The third division in magnitude may be that interpenetrating the atmosphere in gaseous form; the mean annual precipitation is about 120,000 cubic miles—30,000 on land and 90,000 on the oceans, or some 10 per cent of the volume of the atmosphere reduced to liquid measure—which may be regarded as a rough indication of the average content of aqueous vapor. The next smaller division is that gathered largely in polar regions and elevated areas in the solid form (snow, névé, ice); its volume can not well be estimated. The smallest primary division, albeit the most vigorous as an agency of earth-making, is the moving water of streams and springs, sometimes lodging temporarily in ponds and lakes; its volume is negligible in proportion to that of the oceans.

The sea water is a seat of chemical action, including that involved in the development of primordial life, and through both waves and tides an agency of mechanical action in sapping shores and distributing sedi-

ments; while the ground water is effective in solution, ionization, aqueo-igneous fusion, and probably most of the chemical changes in the earth crust, including all those interrelated with vital action. The aqueous vapor mixed with the air regulates or at least conditions all the earth-making processes dependent on temperature—indeed, could that portion be removed without disturbing the rest, the earth would probably be deadened, something like the moon, so as to inhibit life and render ineffective most of the molecular and molar movements of surface and crust. Under special conditions of temperature (itself conditioned by the liquid and gaseous H_2O), the solid phase of the hydrosphere is an effective mechanical agency, gathering in glaciers, grinding rocks, accumulating deposits, and shaping earth forms; chemically, it is inert. The stream water works incessantly, both mechanically and chemically; it has shaped some nine-tenths of the land surface of the globe; it has planed down mountains, leveled continents, transported over and over again a great part of the rock matter of the earth crust, and through transfer of load played a part in epeirogenic movements by which the continents have been extended; and in connection with the rainfall by which it is maintained, it has throughout the ages conditioned vital development and all secondary processes, from the accumulation of soil to the evolution of human activity. Without this smallest but most energetic division of the hydrosphere by which the face of the earth has been wrought into form and fruitfulness, the planetary surface would be a chaos.

GENERAL FUNCTIONS OF THE HYDROSPHERE

Viewed in each of its principal divisions and in some leading aspects, the material of the hydrosphere is homologous with the typical substances of the lithosphere: It yields to gravity and both interacts mechanically and reacts chemically with other terrestrial substances, so that it conforms like other inorganic bodies to the laws of statics and dynamics, and may be treated in equilibrium under hydrostatics and in motion under hydrodynamics; yet viewed as a whole the hydrosphere takes on a significant, or at least suggestive, character which may be likened to the automacy (automaticity of earlier lexicographers) of the organic world and the autonomy of the human world—it assumes a semblance of self-activity in its changes of state and movements in space which tends to facilitate its own working and perpetuate its own efficiency as a planet-shaping agency, for example, in that its presence is necessary to the temperature of the planet which in turn regulates its changes and movements. In this general view the terrestrial H_2O in some measure bridges the break

between (1) that strictly dynamic agency of the inorganic in which actual energy is transmitted or converted and (2) that partly kinetic activity of the organic in which potential energy is actualized and redirected.

Concordantly, the smallest but most energetic division of the hydrosphere (the running water) may be regarded in some measure as kinetic rather than a merely dynamic agency; the kinetic property arising in its interrelations with other substances. Running water does not move uniformly; a film of water on an inclined surface, however smooth, will not remain a film, but soon gathers (*a*) into transverse waves and (*b*) into streams; neither will its movement remain uniform, but accelerates (*a*) in the transverse waves and (*b*) in the medial portions of the streams, and slackens between waves and streams. Similarly, a filament of water descending freely in space breaks up into drops. The variability of flowing water doubtless arises largely in (1) interadjustment among the water particles and (2) friction between the body of water and its bed, while in falling water surface tension and perhaps other factors enter; yet the undulatory tendency is pronounced in small and large volumes in every natural stream and artificial canal—indeed, in all moving water—and the tendency may be intensified when the water carries solid matter. And not only is the stream variable in itself; in a state of nature it introduces variability in its bed—or varigradation—in such manner that all streams of whatever size normally alternate from pools to rapids, and vice versa, save measurably in that case (characteristic of arid regions) in which solid matter so abounds as to overload and spread the water in sheetfloods and debar it from gathering into streams.

Again, streams subject to fluctuation in volume develop inner channels adapted to the lower stages when the water runs clear, and larger channels adapted to the freshets of muddy water with adjacent plains built up and shaped by combined erosion and sedimentation; so that under natural conditions every streamway normally comprises a low-water channel and a high-water channel with a bordering floodplain—a difference between arid and humid conditions lying chiefly in this, that in arid regions the water tends to spread into sheetfloods rather than to gather into streams, rendering the general surface a floodplain and the channel an aberrant feature.

The interrelations of moving water are simple, most of the processes well known; the special significance lies in the fact that the stream no less than the animal makes its own bed, the river no less than the man shapes its own valley, by a complex combination of natural interactions. Indeed, the running waters of the hydrosphere as a whole have shaped

the face of the continents (except when diastrophy, eolation, vulcanicity, or glaciation have temporarily intervened) in harmonic combinations of curves stretching from crests to coasts in graceful sweeps of which each part is adjusted to all others and also to ready movement of the waters—the true Hogarthian lines of beauty, as Van Hise and others happily hold.

SPECIAL FUNCTIONS OF MOVING WATER

The moving stream-water makes its bed and eventually shapes its valley through three primary processes, namely, (1) erosion, (2) transportation, and (3) deposition; and each of these three processes is complex:

1. Erosion (neglecting the more passive processes of disintegration, weathering, etcetera) may be considered as the general process whereby the earth matter is removed by running water from its original loci; it comprises (*a*) solution, in which earth salts are more or less completely dissolved; (*b*) washing, in which finer and softer materials are still further comminuted and softened and floated away; and (*c*) corrasion, in which firmer materials are cut and scoured by the impact of solid particles dropped or driven by the moving water.

2. Transportation may be regarded as the general movement of earth matter seaward by streams; it comprises carriage of material (*a*) in solution, (*b*) in suspension, and (*c*) in what may be denoted *saltation,* the three processes corresponding fairly with those of erosion, since the dissolved rock matter is carried in solution, much of the washed materials (together with the finer corraded particles) are carried in suspension, while the coarser particles due to corrasion (including crushing, grinding, etcetera) and to washing move forward at ever varying rates in saltatory fashion, the variable or leaping movements arising largely in combinations of friction with inertia, as discussed long ago by Hopkins and more recently by Le Conte, Gilbert, and others.

3. Deposition may be viewed concordantly as the general process whereby the transfer of earth matter is completed; it comprises (*a*) precipitation, typically of matter contained in solution on contact with sea water; (*b*) sedimentation, typically the settling of suspended matter on slackening of current; and (*c*) *grounding,* or the more or less temporary dropping and lodgment of particles carried in saltation, typically in sand bars, natural levees, gravel beds, etcetera.

All the main and minor processes blend and measurably alternate in ordinary stream-work, and all are dependent for their efficiency on a variety of factors, of which those most commonly recognized are gravity

(expressed in terms of declivity or slope) and friction; and it may be said to be the primary function of moving water to modify and eventually to regulate the declivity and other factors in such manner as to develop the harmonic lineaments of the earth face—to produce dendritic river systems and paraboloid grades adjusted to the internal harmony of water movement, sculpturing square miles of surface and displacing and replacing cubic miles of earth matter in the course of its work.

REFLEX FUNCTIONS OF WATER WORK

The running water is itself modified by its own work: The matter carried in solution (ordinarily small in amount) adds to its weight, and generally to its volume and specific gravity, while the matter carried in suspension commonly adds to weight and volume and also to viscosity; and generally both modifications are within limits cumulative—for example, the presence of matter in solution may add to the solvency for other substances, and the presence of suspended matter adds to the efficiency in corrasion if not to the capacity for load.

Still more responsive to the work of the stream is the matter carried in saltation; this matter is itself the chief agent of corrasion; with increased volume or declivity, both its amount and vigor of movement increase cumulatively in a geometric ratio; with diminishing velocity or volume of the stream, the saltatory matter and its activity decline geometrically until the stream, as it were, lays aside its tools (virtually disposing of them as building material) and turns from vigorous and chiefly mechanical to sluggish and largely chemical work. While in movement the saltatory rock matter adds to the volume and weight and specific gravity and measurably to the viscosity of the flowing medium; and since it is taken up and laid down at what is frequently paraphrased as the caprice (or will) of the stream—actually its responsion to gravity, friction, etcetera—it, like the matter in solution and suspension, introduces an autonomous factor in the behavior of the stream and thereby transfers the moving medium from the domain of the hydrodynamic into what may be considered the domain of the hydrokinetic—that is, from the merely passive to the partly self-active.

So not only in the large way noted above does the hydrosphere assume an autonomous or kinetic property in regulating temperature and other planetary conditions, but in a special way, through what may be expressed (hardly paraphrased) as exercise of function, that division of the hydrosphere found in running water displays at least an approach toward autonomy and kinesis. As a part of the hydrosphere, the stream

exists and moves; as an agency, it works; as a worker, it modifies both its environment and itself.

MECHANISM OF WATER WORK

The work of the running water (even as autonomously modified) varies with external factors, predominantly declivity: Solvency may increase little with the motion, though it is doubtless rendered more effective by prompt removal of the dissolved matter; washing is facilitated both by the vigorous flow attending high declivity and by the added volume and weight and viscosity of the loaded water, while corrasion is engendered and extended by the mechanical action of the load, especially the part carried in saltation. In transportation the measure of the work increases cumulatively and in a high geometric ratio with declivity and with variability of load, the latter itself consequent on declivity. Failing to discriminate between suspended and saltatory matter (which intergrades in nature yet must be viewed separately in analysis), Dupuit ascribed the carrying of sediment to the differential movement of adjacent layers of the flowing water; though a fairer prima facie view may be gained by conceiving the liquid, like the included matter, to consist of particles moving freely among one another under the combined action of gravity, inertia, impact, adhesion, friction, etcetera. In any event, clear water is practically inert mechanically and incapable of corrasion (so that a jet might play on a solid strong enough to resist its weight with no more effect than a jet of air, though like the air it may be converted into a cutting sand-blast by loading it with corrasive material); still water, too, is practically inert mechanically, though it may carry finely comminuted matter in suspension for an indefinite period (or drop it on the introduction of clear water in such manner as to initiate flocculation), while the transportative power of running water increases cumulatively (certainly within limits) with the speed and differential movement of the water particles attending either (*a*) high declivity or (*b*) large volume.

The competence of running water (using the term employed by Gilbert in his monograph on the geology of Henry mountains to denote the ability of water of varying velocity to move particles of given size) was long ago shown by Hopkins to vary as the sixth power of the rate of flow, though this ratio holds only until the particle begins to move, when it decreases geometrically—that is, remains proportionate to the sixth power of the difference between the velocities of particles and stream (this variability, in which the stationary particle is always subjected to a stronger impulse than the moving particle, contributing to that saltatory movement characteristic of effective stream-work).

Gilbert is once more engaged in a notable investigation of the capacity of streams for load of given size of particle, and is soon to take up loads of variable particles; yet there is thus far no formula for the capacity of streams for loads of the widely variable particles found in nature. In the lower Colorado the load may exceed 5 per cent of the volume or 10 per cent of the weight of the water; in some of its tributaries, when in freshet, the load may temporarily reach 20 per cent of the volume, while in the sheetfloods of Arizona and Sonora the load occasionally increases until the mass becomes a mere mud-bed, gradually coming to rest as the water is partly evaporated and partly absorbed into the earth below. Manifestly the capacity of a stream for solid matter of variable dimensions and weights varies with the velocity much more widely than does the competence. In a general way it may be safe to average the effective competence (that is, the mean difference between the rate of movement of the saltatory particles and that of the stream) at the fourth power, and the capacity for load of variable sizes at something over the competence or sixth power of the velocity; or, since the velocity increases geometrically with the declivity, at something like the seventh or eighth power of the declivity.

Still less is there any formula, or even consistent opinion, expressing that sum of the positive mechanical work of running water (washing, corrasion, suspension, and saltation) which may be denoted *efficiency*, or of the variability in that work attending increase of load; though, manifestly, washing and corrasion must within undefined limits increase with the load. Powell, who raised Lyell's doctrine of uniformism to a higher order and in framing the laws of hydraulic degradation outlined hydrodynamic geology, held that the effectiveness of stream-work must vary approximately as the weight of water and load combined; while Gilbert, whose experiments promise again to revolutionize constructive geology, inclines to regard the carrying of load as commensurate with the expenditure of a corresponding part of the total energy of the stream, thus reducing the measure of transportation to an equation of volume and velocity of the water alone (though it seems probable that this equation should be modified at least to the extent of adding the gravity component and momentum of the saltatory particles, and also a factor for lubrication—an extreme case arising in landslides in which the water acts almost wholly as a lubricant). In a general way the efficiency must vary geometrically with the exercised capacity, that is, the load—say as the second power of the capacity, or, if reduced to actual stream conditions, the eighth or ninth power of the declivity.

The negative mechanical work of moving water (grounding and sedimentation) is beyond the reach of quantitative formulation—at least pending the completion of Gilbert's determinations—but manifestly varies inversely with the velocity and that differential internal movement attending volume. The slackening current assorts its load, according to its power, from boulders to pebbles and on down to sand and silt, chiefly through the saltatory action; the overloaded stream builds bars moving upstream to increase its own head and multiply its efficiency below, and the underloaded stream builds bars moving downstream to increase the head above, and in both cases the movement of the bar material is saltatory and of such order as to initiate and accentuate the alternation of flow from pool to rapid and vice versa. Practically each stream tends to alternate between positive and negative mechanical work in successive instants of time throughout every part of its course, though this tendency may temporarily be interrupted by diastrophic or other derangements of drainage systems. Practically, too, each stream tends to increase also in bank-cutting and bar-building, and generally in the development of curves. In some cases the latter tendency is so strong as to suggest the widespread inference that a curved river can not be straightened, since cutting across an oxbow merely produces extension of other loops until the aggregate length of the river is restored, though Powell established the counter-tendency of large rivers to straighten toward their mouths, and Leighton finds a decided diminution of load within the sinuous portions of the lower Mississippi.

Whatever the ratio of factors in the mechanical work of running water, and however complex and elusive the behavior of streams under natural conditions, the essential fact remains that the internal work of streams varies widely with external factors; and the no less essential fact also remains that this internal work is constantly directed toward the modification of the external factors: In a broad sense, the primary work of the stream is the continuous adjustment of internal relations to external relations (thus conforming to Spencer's characterization of life), with a secondary yet no less continuous readjustment of external relations to internal relations; in a strictly physical sense the stream functions, strengthening through exercise and weakening through inaction, toward the ends of (1) perpetuation of its own existence, (2) continuous growth, and (3) increased facility of work. While all its properties are involved, it seems clear that the distinctive function arises measurably in that primary relation between particle movement and external conditions

which would seem to engender the undulatory motion of the water itself and the saltatory motion of its load.

INTERNAL MOVEMENT OF RUNNING WATER

When viewed broadly in the light of planetary and cosmic movements, the motions of the saltatory particles exhibit instructive analogies, and the analogies extend to the concomitant motions of the water particles: The saltatory particle, whether small or large (neglecting the relatively unimportant case in which rotatory momentum predominates), visibly moves in a downwardly curved path, and its movement is evidently the variable resultant of factors which may be resolved into (1) the primary impulse, or inertia, (2) the resistance of friction, impact, etcetera, and (3) the direct gravitative pull with its inherent acceleration, and (4) the consequent friction; and, considered either with respect to general type of curve or to components involved, the path apparently conforms to those of projectiles, meteorites after entering the atmosphere, and comets on approaching the sun; which paths (trajectories or orbits) approach the parabolic form—that is, the resultants vary as the first and second powers of their components save in so far as friction and other secondary factors interfere. These approximately parabolic paths may be described as *paraboloid,* despite the prior geometric use of the same term in a special sense (etymologically irregular, except as connoting the collective curves of the solid generated by rotation of the parabola). Manifestly if the path of the single saltatory particle is paraboloid, the collective or mean path (or sum of paths) of a series of particles must be similar, since each impact, whether collisional or frictional, merely enters into one or the other factor of the equation and introduces no new order of motion. It follows that all contiguous particles either just ready to enter or just after coming to rest from the paraboloid trajectory must tend to arrange themselves *ceteris paribus* in paraboloid forms, and the illustration of this fundamental law of saltatory movement (and demonstration of the analysis) appears in the prevailing paraboloid curves of land forms shaped by running water.

Now it also seems clear on scrutinizing the motion of saltatory particles of variable sizes in running water that the movement of the water does not interfere with the paraboloid paths, but, on the other hand, conforms in such a way that the paths of all particles from the largest to the smallest visible fall into a beautiful harmony. This concordance inevitably suggests that the water particles themselves move in paraboloid trajectories, each the resultant of inertia, resistance, and gravity, in which case, too, it is manifest that the movements of the sum of particles must

tend to define curves of parabolic order, and that those thrown toward the thread of the current by intercollision must move fastest and farthest. Illustrations of this tendency appear primarily in the paraboloid profiles of mature streams (that is, in hydraulic grades), and secondarily in the prevailing land forms sculptured by running water; the demonstration appears in Humphreys and Abbott's classic determination—the most notable contribution of American engineering to hydrophysics—that the curves of differential stream-flow are parabolic. It follows that stream water may not justly be considered to move in conformable films or even as contiguous filaments, but must be conceived to move as an assemblage of essentially incompressible and noncoherent and both nonattractive and nonrepulsive yet virtually frictionless particles, each responding individually to the forces of gravity and collisional resistance with the constantly varying momenta of inertia arising therein, and all responding interdependently to the sum of these conditions and forces and also to the perturbations introduced by the extraneous particles forming suspended and saltatory load.

The veridity of this concept of the particular mechanics of running water is corroborated by the inability of pure water to corrade, since the particles are themselves virtually frictionless; by the development or intensification of the undulatory tendency soon as the liquid comes in contact with extraneous materials producing friction; by the invariable development of current ripples themselves assuming paraboloid patterns; by the deadening of breakers through load of any material (sand, mud, etcetera) introducing perturbation among the particles; by the geometrically increasing capacity accompanying increase either of velocity or of any load tending to perturb the particles through surface friction, and indeed generally by the natural behavior of moving water. The concept has the merit, too, of explaining physically the paraboloic flow-curves worked out empirically by Humphreys and Abbott, without recourse to arbitrary and probably misleading assumptions as to friction. The concept also clarifies Powell's practical induction as to the increase of efficiency with load; for it is evident that the internal work (neglecting that directly due to wetted perimeter) varies with friction among the extraneous particles—that is, approximately with the aggregate superficies of these particles, capacity and competence varying only with their mass (both with the same velocity function)—while the practical case is that in which the volume is variable from freshet to low-water stage in such degree as measurably to balance velocity and thus eliminate the retardation of flow due to the increased viscosity occasioned by the load. At the same time the concept elucidates the habit of running water to

repel and ground or settle extraneous matter up to a certain point, then after adventitious loading to first gather and later triturate the foreign particles until small enough for grounding, and eventually to clarify itself even more effectively moving than standing, the general tendency being toward the elimination of extraneous or adventitious matter in such manner as to reduce internal friction and consequent expenditure of energy on its way from source to sea—a habit of prime practical importance already discussed by Powell, inferred by Gilbert, and observed by Leighton. Perhaps the chief merit of the concept lies in its relevancy to the classic investigation by Osborne Reynolds into "the circumstances which determine whether the motion of water shall be direct or sinuous," and its sufficiency as an interpretation of his experimental results recorded by the Royal Society a quarter-century ago; for it is manifest that under the condition of little external constraint (such as pressure or declivity) a relatively small number of mutually frictionless particles may adjust their movements to those of a relatively large number of friction-restrained particles, while with either (*a*) increased constraint or (*b*) reduced ratio of friction-restrained particles the normal sinuous (or saltatory) movement must recur—a habit also of practical consequence as the basis of the law governing the flow of water in pipes.

On the whole, the concept of streams as made up of discrete particles moving saltatorily along paraboloid paths simplifies and coördinates views of stream-work under the variable conditions of the earth-face; at the same time it helps to harmonize the physics of the particular movement with both terrestrial and celestial physics in their general aspects.

CONCEPT OF THE WATER MODULE

When viewed narrowly, in the light of various analogies, the general behavior of running water suggests the nature of the water particle: Clearly the discrete particle involved in stream movement can not be a single molecule but must comprise a number of molecules of H_2O, since it must be of sufficient magnitude to undergo the change of state from liquid to solid or gas, or vice versa, without disturbing the atomic bond; clearly, too, the particle can not be an air-formed drop constrained by surface tension, since it is not isolated and also since surface tension itself is due to interrelations of particles (sometimes unnecessarily conceived as molecules); so that, proceeding by exclusion, a discrete aggregation comprising several molecules yet smaller (probably much smaller) than an air-formed drop may be inferred prima facie—an aggregation perhaps of sufficient size to form an invisibly small particle of vapor or a minute spicule of ice with the modification of movement among the molecules themselves induced by change of temperature.

Now scrutiny of streams under the variable conditions of nature reveals striking diversities, presumably due to variability in the nature and dimensions of the constituent particles: The water of a limestone or granite spring is peculiarly transparent yet highly refractive and sparkingly brilliant, notably free and rippling in movement, and manifestly tends vigorously and persistently to exclude extraneous matter by prompt grounding or above-wash floating; the same water, when confined in pools or mixed with surface-flow, soon loses brilliancy and develops an evident tendency to retain and diffuse extraneous matter, which may remain in suspension for hours, days, or even weeks, the difference being so impressive that the million casual observers habitually describe one aspect as living and the other as dead; yet the muddied water (in which the extraneous matter may conveniently be conceived as largely lodged between or among rather than within the water particles) may be induced to clarify itself and at least partially resume its original condition by merely introducing a clear stream such as that of the original spring. The ready inference is that the particles of the spring water are relatively large and free moving, those of the pool relatively small and constrained. This inference is consistent with the conditions under which ground waters gather—that is, in trickles or series of drops each constrained by surface tension and hence of considerable size. It is consistent also with the presumable mechanism of clarification of the muddy pool by a clear stream: When the flocculation of matter in suspension was investigated by Hilgard, and later by Whitney and Cameron, it was found to be affected by chemical conditions, but no adequate explanation was found for the flocculent sedimentation due to the introduction of clear and pure moving water—a phenomenon akin to that of mere introduction of movement, which is well known not only to experimentalists but to every observer of streams (including the boy and even the horse who take supplies from the riffle rather than the pool); yet it is manifest that if the clean particles be larger and freer moving, they will on mingling with the stagnant particles of the pool enlarge the interstices or thicken relatively the films of sediment, and so tend to aggregate the extraneous matter in floccules sufficiently large to escape entanglement and gravitate to the bottom by a sort of mechanical precipitation somewhat like that in which hailstones are formed in the air.

The inference that the tendency toward flocculation inheres in the water rather than the sediment in turn accords with or explains other phenomena: A concurrent inference is that the formation of crystals on freezing is primarily an attribute of the liquid itself, and that the hexagonal forms represent lines of structure or tension at or near the surface of the liquid, which persistently tends to extrude these solids much as it

tends to extrude the extraneous sediment by internal movement, which again is in accord with the cryptocrystalline character and high density of anchor ice formed on stream bottoms in rapids. The concept of the liquid H_2O as itself tending toward hexagonal forms similarly helps to explain various optical phenomena, including refraction in bodies of water, the brilliantly sparkling quality of pure spring water, and perhaps the form of refraction exhibited in rainbows and parhelia and also the behavior of bubbles and foams. The several analogies and inferences lead to the inference that the water particle involved in stream-flow is a discrete aggregation of molecules varying in size from considerably below that of the air-formed drop indefinitely downward; with the suggestion that the particles tend to assume hexagonal groupings at the surface and perhaps on discontinuous planes ordinated therewith, and the further suggestion that when in moderate motion the particles tend to increase in dimensions and concurrently to extrude extraneous matter by flocculation, freezing, etcetera. Manifestly the size of the particle is measurably affected by temperature (as it must be also by electrical tension, etcetera), and it is convenient to think of it in a general way as varying inversely in size with the temperature from a larger aggregation ready to form a crystal of ice to a smaller aggregation ready to sever gravitative bonds and float into the air as a vapor particle.

In connection with this view of the water particle, it is noteworthy that while the hexagonal tendency in water is so strong that crystals formed by freezing will, as shown by Tyndall, normally assume no other form, and that groups of bubbles are, as shown by Boys, stable only when every point of complete contact is made up of three edges and six planes, each pair 120° apart, the hexagonal structure is essentially bi-dimensional and the structural units will not fall into stable or equipotential forms in the tri-dimensional relation. Conformably, a special series of experiments kindly conducted by Cameron and Free show that when similar and equal spheres, such as shot (which if compressed in a single layer tend to form similar hexagonal prisms), are brought together en masse they tend first to gather into groups hexagonal on surfaces and occasional discontinuous planes within, and that when further compressed they tend to lose the hexagonal type and form indefinitely variable polyhedra, somewhat approaching yet never attaining either the rhombic or the pentagonal dodecahedron or the icosahedron, and indeed display what may be considered an inherent tendency toward differentiation. All observations indicate that if the water particles are uniform and regularly spheroidal or polyhedral (though not cubical, which is inconceivable among cosmic types) and form stable combinations in the bi-dimensional relation or in a single layer, they can not form stable combinations in the tri-dimen-

sional relation, and vice versa; and observations and analyses which need not be followed in detail indicate that the general proposition is true regardless of the forms of the particles, provided they be similar and equal (excepting, of course, the cube, which is variable in the internal gravitative relation). This innate incongruity (or incompatibility) of bi-dimensional and tri-dimensional relations is highly significant; it would seem to explain directly the virtually endless instability of liquid H_2O and go far toward explaining the apparently inherent undulatory property of water and the relation of this property to the saltatory movements of its included particles; hardly less directly it would seem to offer a physical explanation of liquidity as a state of matter, while indirectly it would appear to lie at the foundation of (or at least extend coterminously with) Spencer's generalization as to "the instability of the homogeneous" among planetary phenomena.

The same innate incongruity in the bi-dimensional and tri-dimensional relations, coupled with consequent instability in suspended and saltant contents, is attested by the peculiarly automatic behavior of natural and artificial bubbles, which readily unite in hexagonal forms on a plane surface, but with further combination become mutually destructive or at least unstable, and in their instability (as in Bütschli's experiments with oil-foams) display such properties as streaming and contractility passing into motility, et al., simulating those of protoplasm in extraordinary degree. In the visible internal movements of the oil-foams and soap-bubble groups there is a tendency toward differentiation in size of the constituent units manifestly due to interadjustment of external and internal stresses; the persistence of such interactionary tendencies is illustrated by the behavior of foam-clots in eddies of streams rendered viscid by sediment, which grow below by capture of bubbles as the upper layers rupture by evaporation, roll and overturn with the shifting center of gravity, coalesce with other clots, multiply by fission, and continuously undergo deformation and transformation, yet as masses retain measurable integrity for hours or days; and this behavior of the heterogeneous units and groups can hardly be wholly inconsistent with that of the homogeneous units attested, for example, by Mendenhall's demonstration of liquidity by means of suspended eggs, in which, both being set in motion alike, the raw egg continues in rotation and swing long after the boiled egg comes to rest.

On integrating these and other indications of the inherent properties of the water particle a final concept is gained, in which that particle is a structural unit composed of a number of molecules varying with temperature and other molecular stresses but responding individually to gravity and molar stresses (as in streams, waves, tides), each tending to assume the hexagonal form at surfaces or in single layers and all tending to

assume irregular polyhedral forms in masses, collectively tending also to spread into single layers under gravitative and other stresses and through the consequent interactional movements introducing indefinitely continuous internal motion of undulatory character in all masses of more than a single layer, each unit being individually susceptible of moderate deformation but otherwise incompressible and inelastic (without molecular rearrangement) and in the collective aspect mutually frictionless and neither attractive nor repulsive; the constituent molecules being capable of incorporating alien atoms, but the units being capable of incorporating extraneous particles only through frictional contact with the foreign surfaces and thereby becoming collectively viscid, with the counter-capability of facilitating gravitative separation and clarification and thereby restoring complete liquidity by their own internal movements, the aggregations of units thus tending to maintain their own integrity by continuous mechanical adjustment between their own and the alien particles; the dimensions of the units being determined (measurably as in air-formed drops) by the balance of internal stresses against external stresses. Since the unit so conceived is the ultimate quantity of H_2O capable of functioning in the characteristic ways and is at the same time the prime determinant of the rhythmic movement of H_2O in masses, it is the natural measure and modulator of moving water and can hardly be denoted otherwise than as the *module* of H_2O.

While the analogies and inferences indicating the nature of the water module are less definite than is desirable, they nevertheless combine to yield a concept which is not only worth considering in itself, but would seem infinitely more accordant with the sum of terrestrial phenomena than the concepts of water moving in films or filaments or in separate molecules, hitherto frequently held merely for lack of better. SOME concept is necessary as a basis for practical applications, and this seems to be in accord with all of the more firmly established hydrologic facts. In turn it indicates a useful direction of approach in dealing with the more pressing problems of hydrology, including soil-erosion, bank-caving, bar-building, silting, flocculation, clarification, etcetera, with their applications; at the same time it helps to explain in a simple and rational way the nature of that habitual interadjustment of internal and external relations which imparts to moving waters their seemingly autonomous character, and aids in harmonizing terrestrial and celestial mechanics in such wise as to suggest new homologies and open new lines of research.

CUMULATIVE CHARACTER OF WATER WORK

Conformably with the undulatory and saltatory properties, the virtually autonomous work (or functioning) of running water is accelerative in

extraordinary degree: When the effective competence varies as the fourth power and the capacity as the sixth or seventh power of the flow and the efficiency as the eighth or ninth power of the declivity (and the general relation holds, regardless of the precise ratios remaining to be determined), the correlative factor is time; so that in any formula for the hydrokinetic function, time will vary with a power of work so high as to render the former factor comparatively unimportant. Similarly, the mechanical work of the standing water forming the dominant division of the hydrosphere is extraordinarily accelerative, according to the combination of external conditions (wind, tidal stress, bottom-friction, etcetera) with the undulatory property. Perhaps the most effective function is wave-work, which, like stream-work, tends to plane the lithosphere toward such uniformity as to reduce its own energizing, as when waves augmented by sea cliffs sap the cliffs and eventually remove the cause of their own strength, while a single great wave may displace a larger rock than all the average waves of a year, or those of a single storm may outwork the mean waves of a decade; the tides are notably cumulative, and doubtless react on the terrestrial rotation; while winds and tides cooperate in generating powerful currents which work cumulatively in distributing both sediments and heat. Both in running and in standing water the acceleration of work is cumulative in a geometric ratio, and so far resides in the undulatory property of the liquid as sometimes to appear disproportionate to the direct physical causation; and it is partly in this respect that the behavior of moving water takes on the kinetic or autonomous aspect, likening it rather to organic activity than inorganic agency. Yet the striking fact remains that both running and standing water work at a rate conditioned if not initiated by environment for such reconstruction of that environment as to fit it for the ready and harmonious movement of the medium itself, much as the aqueous vapor in the atmosphere automatically (or autonomously) regulates the temperature requisite for its own maintenance.

In a general way, the virtually autonomous and accelerative property of moving water conditions geologic process in its mechanical aspects: Degradation and aggradation are measures of agency rather than time; vertical miles of littoral sediments may be accumulated along continental shelves, while the abysmal depths gather material so meager that most of the mass is organic residua or meteoritic waste; while geomorphic sculpture measures declivity a thousand-fold more accurately than time, so that the 300-foot post-Lafayette (or Ozarkian) gorges of the Appalachian rivers may have been cut while a fraction of one foot was washing from the average surface of the intervening plains. In the broad sense, geo-

logic product attests process and not time; for under its undulatory property the predominant agency introduces at least the germs of kinesis and cumulative autonomy, rising so far above inert interrelation as apparently to bridge the chasm between the typically physical and the nascently physiological.

ROLE OF WATER IN THE ONTOSPHERE

A relatively minute fraction of the terrestrial H_2O is withdrawn from the distinctive divisions of the hydrosphere and incorporated in living organisms—that is, accumulated in what may be denoted the *ontosphere;* and in this association its behavior is strikingly parallel to that manifested in running streams. In plants a widely variable but always considerable portion of the organism is made up of water; the circulation involved in tissue growth is wholly dependent on water moving in a manner measurably analogous to stream-flow, carrying material in solution and suspension if not in saltation, traversing cells in a manner simulating the alternation between pools and rapids in streams, and partly flowing in ducts so arranged as to suggest river systems with their automatically shaped banks and natural levees—for example, in leaves, in which the dendritic vein systems have become progressively more economical during the ages of phytic growth from calamite and ginkgo through lanceolate and lobate types to the deeply digitate forms of later eons. The source of the power involved in maintaining vegetal circulation is doubtless evaporation from the stomata, coupled with capillarity and osmosis in the vascular system extending from roots to leaves, the pull presumably equalized throughout by surface tension; and while the circulation may have little or no effect in maintaining the temperature of the organism, many structures have become so adapted as to permit congelation without injury to those plants and products that survive seasonal changes. In animal bodies the quantity of water is less variable but generally large, averaging some 75 per cent of the weight of the body in the higher orders; the office of circulation is extended, so that the liquid is loaded with corpuscles and phagocytes and other particles themselves bearing or being materials of tissue growth and waste, and is typically moved by adaptively developed structures in the undulatory (or pulsatory) way characteristic of streamflow; while the rate of movement and the capacity for load of the circulatory fluid are regulated by autonomously evolved structures in such manner as to control (increasingly from lower to higher forms) the temperature of the organism independently of exterior conditions, much as the atmospheric vapor regulates the temperature of the planet independently of that of interstellar space.

The correspondences between vegetal and animal functioning and the virtually autonomous work of moving water are too many and perhaps too indefinite for enumeration; yet a fundamental likeness appears in a circulatory mechanism so adapted as to adjust internal relations to external relations continuously, and eventually to reduce external conditions to conformity with internal conditions. The organic functioning indeed attains a higher order of autonomy, a more complex form of action, a more continuous type of structures, and the coordinating attribute of vitality; yet it may be seriously questioned whether the differences are not of degree rather than kind—and it may not be denied that the analogies (or homologies, if the correspondences be regarded as such) arise chiefly in the pulsatory property of water.

It is significant that while the aggregate volume of the ontosphere (including the H_2O forming its major portion) is small, its efficiency in modifying the earth face is disproportionately large: The rate of geologic process on each part of every continent is largely controlled by the flora and the soil which the floras of the ages have accumulated, while during each eon the flora itself has been modified and started toward reconstruction by the fauna, as when the cryptogams of the Paleozoic were set on the way to decadence by flower-seeking and pollen-bearing insects, when fruit-bearing trees were placed in the lead by the help of seed-scattering birds, and when man appeared to cultivate the innocuous and exterminate the noxious among the fruits and grains and tubers.

Considered in the planetary aspect, the functions of the ontosphere merely raise to a higher plane the agency of the hydrosphere in regulating terrestrial conditions and shaping terrestrial progress; and both planes are parallel with those next higher, in which the attributes pertaining to both merge in still more complete autonomy. In a broad way, it is the function of the hydrosphere to propagate motion (molar and molecular) and form structures, and the function of the ontosphere to propagate both motions and structures; while the structures are distinct, the laws of the motions have much in common, and the functions of both spheres involve at least measurable self-activity and tend alike toward self-perpetuity.

THE FIELD OF HYDROGENY

While terrestrial organisms are primarily dependent on the presence of terrestrial H_2O in such abundance as to be fairly free of inorganic chemical and mechanical restraint, certain organisms at least produce (or reproduce) H_2O through their own vital processes: In assimilation by higher animals, carbohydrates (for example, starch, cellulose, sugar, some

fats, etcetera) are decomposed in such manner as to yield H_2O and CO_2, the latter in quantities affecting the atmosphere in buildings and even in cities, and the former in a corresponding ratio which has received less attention; and certain organisms of arid regions have acquired the faculty of dispensing with free water, apparently depending wholly on this internal source of H_2O for the maintenance of their vital functions, as in the case of the desert mice recorded by Coville. While vegetal assimilation is generally confined to simpler compounds, certain desert plants living on hydrated rock-matter have acquired highly developed structures and vital processes adapted to the arid conditions (including notably abundant starch and cellulose in their tissues), and apparently produce (or reproduce) at least enough of the H_2O employed in the solution and elaboration of substance and maintenance of circulation to prolong their vital functioning through rainless months and years.

Considered as a planetary constituent, the water contributed by organic agency is not only inconsiderable in amount but probably a mere restoration of H_2O temporarily tied up in terrestrial compounds; yet, regarded as a planetary process, the generation (or regeneration) is most significant, in that it marks a distinct type of interrelation in which organic activity attains a higher order of autonomy and initiates a more effective control of potential and adjustment of internal relations to external relations than pertains to the planes of stream-flow and circulation, though again the difference is of degree rather than kind. The general process may be denoted *hydrogeny;* for, even if it involves (as seems probable) nothing more than the liberation of locked-up material, it appears to open a natural way toward the perpetuation of the ontosphere through its own functions in a manner somewhat like the ways in which the hydrosphere perpetuates the balance among its own states and divisions through temperature control, and in which streams perpetuate their own valleys through rock-transfer. In relation to the external, stream-work is ephemeral, organic agency individual and generational; while the hydrogenetic function spans secular time and embraces latent potentiality.

Applications of Hydrology

Functions of the Psychosphere

Viewed broadly, it is the function of organized intelligence to control natural powers—the powers comprising both molar movements and those molecular motions determining the properties of materials, the means of control including those suggested by natural interrelations, and the organ-

ized intelligence (chiefly human) constituting the psychosphere; and the function is and must be exercised primarily through the ontosphere: Here the psychosphere and hydrosphere touch and interact, and here telesis arises; and while in assuming control of the terrestrial H_2O men began as mere organisms, they have advanced through successive stages by means of the collective action attending social and industrial development toward the end of complete control through a perfected hydronomy—an end not yet attained on any part of the planet, although coming definitely into view through scientific prevision. The stages of advance fall into a natural order, which is at once logical and historical:

USE OF THE CORPUS

The initial stage in utilization is that of water-supply first for organic and later for industrial needs, both tending toward increased control of the natural H_2O: The earliest uses were for individuals and families, followed by uses for stock and agriculture and then for manufacturing; of late, uses for communities and cities have arisen, and state and national uses are in prospect. The basis of the stage is the substance or corpus of the surface and ground water, which was first drawn in common from chance sources, and hence came to be regarded as a prime necessary of life and not an object of property; and when wells were made and springs improved the proprietary right was frequently deemed to inhere solely in the appurtenances, either including or not including the circumjacent land. With growing population, certain sources were gradually brought under protection and the water was clarified and purified with a view of preserving the health of communities (for H_2O is the foremost human and stock food, forming fully four-fifths of the normal dietary and constituting a corresponding proportion of the normal body); and in populous communities both the sources and the water have become the objects of inchoate or established proprietary right, the title usually vesting in the municipal or other community; for in this, as in many other respects, states and nations lag behind individuals and communities in recognizing fundamental interests.

The average adult ingests about five pounds of water daily; the average daily consumption for all purposes in cities ranges from 10 to 200 gallons per capita, generally increasing with the size of city and appreciation of hygiene; the 1,500,000,000 inhabitants of the world probably use a cubic foot (some 8 gallons) apiece daily for necessary purposes, or an aggregate of about 550,000,000,000 cubic feet (3.73 cubic miles) annually, or about 1/364 of the mean annual rainfall (200,000,000,000,000 cubic feet) on

mainland United States; the cost, both absolute and relative to other elements of the dietary, varies widely.

NAVIGATION

The earliest stage in the collective utilization of water is that arising in navigation: Long before written history began, the continents were peopled through migrations along shores and streams, and most of the primitive peoples were more or less adept in the use of water craft; later, exploration and settlement followed waterways, and the leading countries of the world have adopted regulations for ocean and lake commerce and have entered on the control of rivers and the construction of canals for inland navigation. The basis of the stage comprises the 142,000,000 square miles of water surface on the globe, and the 6,000 cubic miles of river water flowing seaward annually from the 55,000,000 square miles of land surface. Originally common to all, the oceans may be said to have passed under commercial control, largely national and international, though little progress has been made (save in certain harbors) toward physical control. The rivers and lakes are generally used in a nominal degree for commercial purposes by the nations in whose domains they lie, and in a relatively small number of rivers (with a few canals) physical control has been undertaken, usually through the transfer of material by excavation and filling—that is, by processes for which moving waters are the natural and by far the most effective and economical agency.

Water affords the most economical means of transportation, and in a general way oceanic commerce increases geometrically with the growth of the world's population; in some cases inland navigation increases with population, in others it declines either temporarily by reason of economic conditions or more persistently through indifference or inefficiency of states and nations. In no country has complete control of navigable and source streams been undertaken in the interests of mankind, though in America a general plan for doing so has been approved by the chief administrative authorities of states and nation.

POWER

The next collective stage is that of power arising in natural movement: Stream-flow and oceanic currents were utilized to facilitate navigation in the earliest times, and many primitive peoples derived from waterfalls and rapids the power required for certain rude industries; later undershot and breast and overshot water-wheels were perfected, and sluices and dams and reservoirs were devised to utilize the natural head first of

smaller and later of larger streams; still later turbines were installed and entire rivers were brought under control; while in some cases tidal ebb and flow were turned to work, and wave-motors were invented. The chief basis of the stage is the 6,000 cubic miles of stream water annually descending from an average altitude of 2,300 feet over the 55,000,000 square miles of the lands of the globe (equivalent to 6,500,000,000 theoretical horsepower, or perhaps 20 times the aggregate steam-power, animal-power, wind-power, and man-power used throughout the world); a secondary basis is the tide-power and wave-power of oceans and sounds, seldom available under existing economic conditions albeit a vast prospective resource; while an indirect basis is sun-power, of which the availability is absolutely conditioned (as indeed is human and all other terrestrial life) on the aqueous vapor in the atmosphere.

The direct utilization of water-power entered on a new era within a decade with improvements in electrical transmission. While no people has thus far undertaken the systematic utilization of this interest or established the proprietary rights arising therein, the leading nations are awakening to its importance, and in America a national policy of complete water utilization (including power) has been foreshadowed as an essential of national perpetuity.

DIVERSION

The fourth stage in utilization is that of diversion of the natural movement of water by artificial means for human ends: Even in prehistoric times the natives of India, Peru, and other lands diverted streams either for direct water-supply or for increasing the fruitfulness of lands chiefly by irrigation; and reclamation by irrigation or drainage or both combined (for the processes are correlative) is more or less extensively employed in several countries, while in arid regions generally and in some humid regions the natural waters are at least partially diverted and redirected toward agricultural ends. Of late the purposes of diversion are multiplying apace; municipal storage and purification; the development of power, both directly and through steam; the direct application of power as in hydraulic mining and excavation; the transfer of material in suspension and saltation in connection with dredging and jettying and in warping and filling; the transfer of material in solution as in salt extraction; the transmission of power as in hydraulic presses and elevators; the transmission of thermal energy for heating or cooling buildings; and even the utilization of proper terrestrial heat and quiescent vulcanicity by means of circulation through deep borings—these are among the multifarious purposes.

The primary basis of the fourth stage is the 30,000 cubic miles of water annually distilled from the clouds over the lands of the globe, of which amount some 50 per cent is evaporated (thus serving to temper climate), while an average of some 20 per cent flows seaward in streams, and perhaps as much more becomes ground water, leaving a considerable fraction to be consumed in organic growth or inorganic chemical combinations; the secondary basis (in both positive or injurious and negative or beneficial aspects) comprises the earth-matter carried into the ocean in solution, in suspension, and in saltation—that is, about 1 cubic mile, 20 cubic miles, and say 3 cubic miles respectively every year.

In humid regions generally the primary water-supply is disregarded or deemed appurtenant to the land and the off-wash is complacently ignored, while in arid regions men early began to realize that productivity and even habitability are dependent on the retention of water and the prevention of wash; indeed, under the bitter strife for existence amid sun-scorched sands, water became a vital currency, eventually engendering an altruism which ripened into world-civilization and spread from the deserts of the globe to blend in modern culture.

Partly by reason of the fundamental differences between humid and arid regions, the customs and laws of the world's nations respecting the control and use of water are diverse: Several states among the world's countries provide for the appropriation (or expropriation) of water, for the diversion of streams, and in same cases for retaining storm waters in reservoirs; in a few cases forestation or other agricultural devices have been adopted at least partly to equalize stream-flow by diminishing storm run-off and increasing the volume of ground water; but the development of a common-law doctrine on a practically riverless island in a humid zone, with concomitant juridical precedents and procedure on differently conditioned continents, has greatly retarded recognition of the real interests involved, and it is only recently that a comprehensive system has been proposed for the control and utilization of the entire water-supply of a single nation—the United States.

The modern plan contemplates complete diversion—that is, artificialization—of the natural water movement both on and below the surface, in such manner as (1) to prevent floods by so managing the soil and soil cover that the local rainfall will be absorbed where it falls; (2) to spare the soil, and so save the stream from contamination; (3) to increase productiveness by checking erosion and securing better distribution of the ground-water; (4) to equalize and clarify the streams by preserving and maintaining ground-water seepage, as well as by diminishing freshets; (5) to coordinate works connected with water-supply, navigation,

power development, irrigation, drainage, and other purposes in such manner that each will form a part of an interdependent nation-wide system; (6) to utilize the natural corrasive and transportative power of streams for their own improvement; and (7) to so extend navigation and water transportation as to meet the multiplying needs of increasing population.

PRODUCTION

The final stage of water utilization is prospective rather than present; it pertains to hydrogeny—the actual production of water through organic decomposition of compound substances: The production of water at will promises to mark one of the two greatest steps in the human aspect of planetary development; the earlier step was the conquest of fire (undoubtedly beginning with mere associative use, passing to diversion, and ending with nearly complete creative control), which separated even the lowest man from the highest beasts and permitted progressive utilization of natural chemical reactions in which relatively complex compounds were reduced to relatively simple form in such manner as to yield useful energy with useless byproducts; the later and largely prospective step is the subjugation of water (already under way through associative use, now passing to diversion, and destined to advance toward complete and perhaps creative control), which will undoubtedly permit eventual utilization of natural chemical reactions in which relatively complex compounds are reduced to simpler form in such manner as to yield a useful byproduct with immaterial expenditure of energy. The possibilities are vast, but thus far too vague to be pursued—at any rate beyond such prophetic indications as (1) Burbank's inventions of novel or improved cacti capable of collecting and storing effective quantities of H_2O available for the sustentation of stock in arid regions, and (2) McDougal's novel applications of these water-storing organisms as soil-media for the growth of other plants (thereby literally performing the miracle of producing grapes from thorns), which seem to open the way to conquest over the world's deserts for human weal.

EPILOGUE

Summarily, the terrestrial H_2O, or hydrosphere, envelops the entire planet in the five natural divisions of sea water, ground water, aqueous vapor, ice, and stream water; in an automatic (and virtually autonomous) way it so controls planetary temperature as to maintain in slightly variable yet effective proportions its own liquid, gaseous, and solid states; in contact with other substances and in some measure inherently, its

motion is undulatory or pulsatory, and in streams it moves extraneous matter in a saltatory way, thereby automatically (or autonomously) adjusting internal relations continuously to external relations and eventually adjusting the land surface of the planet to its own movement; in streams, and measurably in lakes and seas, it consists of inert and inelastic frictionless particles or modules of variable size, inherently incongruous and unstable among themselves, each tending individually and all tending collectively to move saltatorily in paraboloid paths adjusted to gravity and friction with bed and load; it enters into and forms the greater part of terrestrial organisms, which also adjust internal relations continuously to external relations and tend to direct both internal and external physical processes toward their own perpetuity and toward a progressive control of the terrestrial H_2O itself; and through organic function it forms a prime requisite for organized intelligence, which continually readjusts internal relations of organic and other materials and powers to the sum of external relations in such manner as to increase its own control over planetary conditions and thereby perpetuate its own existence with that of the organisms and the menstruum on which they alike depend. On these and related elements scientific plans for the utilization and ultimate control of the terrestrial H_2O may safely rest; and on these and related scientific plans in turn the hopes of men and nations for their own prosperity and perpetuity may confidently be founded.

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GEOLOGICAL HISTORY OF THE REDSTONE QUARTZITE[1]

BY FREDERICK W. SARDESON

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INTRODUCTION

Redstone, as it has been called for an indefinite number of years, is a conspicuous hill of quartzitic rock in the valley of the Minnesota river, midway between the towns of New Ulm and Courtland. The aim of this paper is to describe, geologically, this Redstone and the region which immediately surrounds it. The name Redstone, as used here, has never been employed as a geological formational name, and in the present paper it will be used for the particular hill, Redstone, while the term Courtland quartzite is the geologic formational name of the same rock. The old village of Redstone, which stands at the foot of the quartzite hill, has taken its name from that of the rock, rather than the name of the rock from that of the village.

The Redstone quartzite outcrops in an area of about 2 square miles east of the village of Redstone, on the left side of the Minnesota river, along the railway from New Ulm to Courtland, Minnesota. It is a conspicuous feature in the valley because the hill of rugged quartzite rises

[1] Manuscript received by the Secretary of the Society March 23, 1908.

about 175 feet high above the river's level and extends out from the northeast side of the valley so far as to turn the river from a direct course. The valley widens opposite this quartzite barrier—that is, on the other side of the river. None of this quartzite is seen on that side of the river and no such outcrops of it appear elsewhere along the valley, so that the Redstone has the appearance of an isolated block.

On the north side the quartzite extends under glacial deposits at the foot of a scarp which is the side of the valley. The highest point on the Redstone quartzite hill is in fact below the general surface level of the glacial drift on either side of the valley, and its position is such as to clearly indicate that it was once covered by glacial deposits, and that its uncovering from the drift has been due to the great glacial river Warren, which excavated the Minnesota valley to its present size. The quartzite being very resistant to erosion, the great river, which at first flowed over Redstone hill, later worked out an easier course around the south side of this rock mass. The Redstone quartzite has thus been left obtruding above the bottom of the valley. In similar manner, river silts of Cretaceous age, on the sides of the quartzite mass, show that in that age also it formed a prominence above a river. The Cambrian sedimentary rocks in turn appear as laid down about its foot, on the shores of an encroaching sea.

The Redstone, or Courtland quartzite, has therefore this distinction, that it stands in close relation, although unconformably with recent and Pleistocene deposits, with Cretaceous and with Cambrian, as well as with supposed Archean formations. These diverse formations are unconformable also, each to the other. The geologic history of the Redstone quartzite mass is to a large extent a key to the geologic history of the surrounding territory. Detailed account of these formations and their relations is given in following chapters.

In regard to literature concerning the Courtland quartzite and the formations about it, the work of C. W. Hall, Warren Upham, N. H. Winchell, and Leo Lesquereux are important. The first named author has summarized all the earlier literature on the quartzite and the granitic or gneissic rock in particular, and the other authors named embody the knowledge of the Cambrian, Cretaceous, and Pleistocene formations. A list of the works to which reference has been made is found at the end of this paper.

For opportunity to study closely the geologic formations around New Ulm, Minnesota, I am indebted to Dr O. C. Strickler and the New Ulm Commercial Association. For assistance and valuable geologic information, I am under obligation to Mr Benedict Juni, of New Ulm.

The geologic field about the Redstone and the neighboring parts of the Minnesota and Big Cottonwood valleys has proved to be an inviting one. Each of the geologic formations demanded more complete investigation than had been accorded them before, partly by reason of advance in knowledge of correlative rock formations in neighboring regions which have been studied by geologists since the above-mentioned works were published and partly by reason of discoverable new evidence and needed correction of previous observations. Advance, which has been making in the knowledge of the "Iron ranges" and of the Baraboo, Wisconsin, region in particular; the changed interpretation of the Dakota sandstone formation, and the question of distinct glacial periods demanded review in relation to this region. Some rock exposures which had been called Cretaceous are found to be altered Archean granitic rock. A volcanic dike has been newly discovered in the Courtland quartzite at Redstone, and this affords good evidence on the question of structure and induration of that rock. Quartzite conglomerate is found to be Cambrian and not contemporaneous with the Courtland quartzite. The Cretaceous strata of wide extent are found to be fluviatile and lacustrine in origin rather than the product of the "Cretaceous ocean." The glacial deposits show two distinguishable till sheets with evidence of pre-glacial and inter-glacial valleys corresponding to the present Minnesota. As already indicated, the Redstone quartzite is of paramount interest in itself, besides having an important relation to the other formations. The accompanying geologic map (figure 1) shows the extent of the geologic formations.

The Archean or granitic Rocks

Two areas of granitic or gneissic rock appear in the region about Redstone. One of these is on the Big Cottonwood river and the other on the Minnesota. The former is the larger, but has not been before described excepting by Upham and Winchell. Upham refers (*6*,[2] volume 1, page 574) to it as a Cretaceous clay forming the base of a "section on the Cottonwood river south of New Ulm," which he cites from Winchell. It is described as follows:

> "4. Fine somewhat gritty clay, largely aluminous. This is white and, when long submerged, soft and fluid-like, but when dry has to be quarried by blasting. This, mixed at the rate of two-thirds with one-third of No. 3, makes a fine, white firebrick—seen 12 feet."

This rock is in truth an altered or rotted granite *in situ*, rather than a Cretaceous clay. It has been bored into about 15 feet below the level of

[2] Figures in italic refer to citations at the end of this paper.

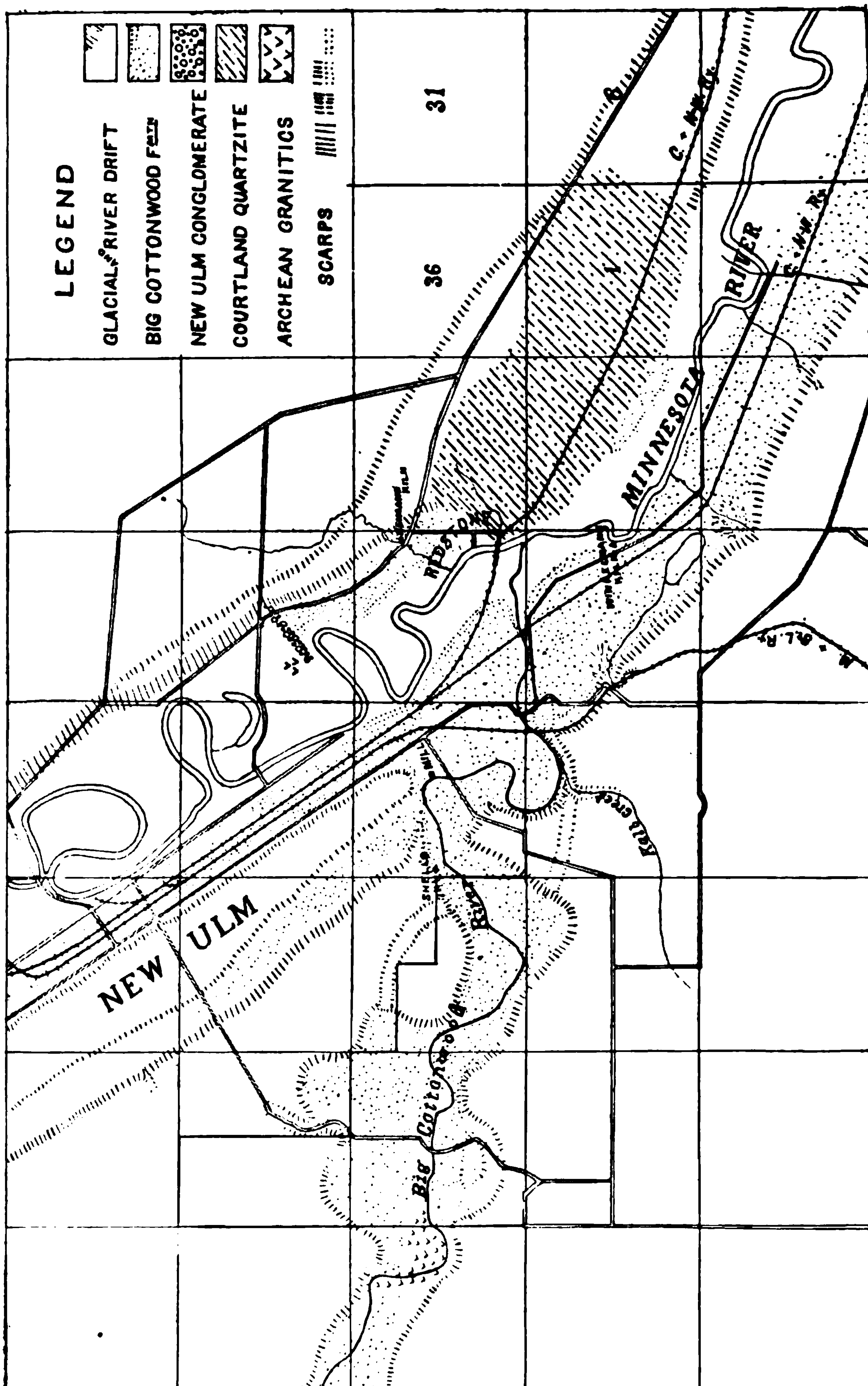

FIGURE 1.—*Geologic Map of Redstone and the Region near New Ulm, Minnesota*

the river and is seen 10 or more feet above the river. It recurs in outcrops for half a mile down the river from the point, referred to by Winchell, where the brick were made. It consists of angular grains of quartz and small ferruginous concretions embedded in a kaolin groundmass, which is evidently altered feldspar, etcetera. The rotting of the granite will be discussed in considering the Cretaceous. The depth to the unaltered granitic rock has not been determined, but I have mapped the area as that of a granitic rock (see figure 1), where only recent alluvial deposit covers it.

The area of granitic rock outcrop in the Minnesota valley lies at the margin of the floodplain of the river, on its left (east) side, opposite New Ulm. This is practically unweathered rock and, as well described by C. W. Hall (*10*, page 25), it is "granitic in texture, of medium coarseness, somewhat porphyritic, and of reddish color, due to the abundance of red feldspar. It is hornblendic, but contains only a small portion of basic constituents, ..." Veins of white quartz 1 to 8 inches wide occur in it. The freshness of the rock here is due, I think, to the protection of a former covering of quartzite conglomerate which is seen outcropping still at 150 paces to the east of it. The surface of this exposure reaches to about 800 feet above tide, while that on the Big Cottonwood reaches nearer 850 feet. In the city wells of New Ulm, granite is said to have been struck at the depth of 190 feet—that is, at 650 feet above tide. At Shell's brewery, on the Big Cottonwood, it was not so deep. Evidently the granitic rock has an uneven surface and is yet of wide extent. Presumably it lies also under the Courtland quartzite, but at what probable depth will be considered in discussing that rock. Further, the erosion of the granitic rock and the alteration of its superficial part will be discussed in relation to the Cambrian and Cretaceous formations. The age of this rock is here assumed to be Archean.

The Courtland Quartzite and the Porphyry Dike

The ancient name Redstone could not be used for the quartzite formation of the Minnesota valley without confusion in terminology and it has not been adopted, although otherwise it would have been a very appropriate name. The term New Ulm quartzite is found in "North American Geologic Formational Names,"[3] where its origin is accredited to Winchell (*5*, volume 2, page xxii). It is, however, not evident that Winchell intended to introduce a new formational name. When he used the words "New Ulm and Pipestone quartzites (Potsdam)" he rather in-

[3] F. B. Weeks: Bulletin no. 191, U. S. Geological Survey, 1902.

tended, I think, to say Potsdam at New Ulm and Pipestone. In the same volume in which this expression just quoted was used, Upham (*6*, volume 2, page 157) calls the formation "Potsdam conglomerate and quartzite," thus following Winchell, who says, in the preceding volume (volume 1, page 537), of the quartzite of Pipestone: "probably the equivalent of the New York Potsdam sandstone, but which Dr C. A. White, of the Iowa survey, has designated the Sioux quartzite . . . ." As formational names, the terms New Ulm and Pipestone would be at once synonymous with each other and with the name Sioux quartzite, and all these three with "Potsdam," according to Winchell, and it seems improbable that he intended to introduce the former as formational names. At a later date (*9*, page 157) Winchell says:

"This seems to prove that the Sioux quartzite, the New Ulm quartzite, the Baraboo quartzite, and the Barron County quartzites are of the same age. . . . ."

They are that which Wisconsin geologists have called Huronian, as Winchell also pointed out. Whether the words New Ulm quartzite were intended or not as a formational name, Winchell included under it two distinct areas of rock exposure, which now appear to be of very diverse age, namely, the quartzite at Redstone, in the township of Courtland, between the town of the same name and New Ulm, and the quartzite conglomerate seen near New Ulm.

Reference of the Redstone quartzite to the "Huronian" or to the "Potsdam" is not definite enough, and even the term Sioux quartzite, though undoubtedly applicable, is not such as to preclude the use of a term of narrower definition. I propose therefore to use the formational name Courtland quartzite here, with the understanding that the type locality is the Redstone near New Ulm. The name New Ulm will apply to the quartzite seen opposite that city.

Considering the Courtland quartzite, this formation at Redstone has been displaced and then profoundly eroded; so that the surface, which rises in a series of exposed scarps and soil-covered terraces from the river to the summit of the hill, is estimated to cross some 300 feet of strata in 150 feet elevation. The northern part of the area shows the lesser dip, and the southern side of the area shows the greater dip, so that in crossing it from north to south the general impression to me is that of approaching a great fault from the downthrow side.

C. W. Hall (*10*, page 22) finds, from an average of many observations in diverse places, that "the strike of the quartzites is north 60 degrees to 70 degrees west, and the dip varies from 5 degrees to 27 degrees north."

Both cross-bedding and minor faulting interfere in the measuring of the dip. The most distinct evidence of faulting I discovered in a dike.

Dikes have not been heretofore reported here, though they were to be expected. The one which I have discovered is on the north side of the railway cut, in the quarry of the New Ulm Stone Company. It appears as a clay seam, a foot wide, perpendicular to the bedding of the quarry rock and crossing the quarry north 25 degrees east. It is exposed some 20 feet from the surface downward. The clay is dove-colored, with rhombic patches of white, marking it as a rotted or altered feldspar porphyry. The east or hanging wall is slickensided, and the dike is brecciated or crushed near it, so that white patches are drawn out into irregular seams, from which I infer that faulting had taken place parallel to the dike before the porphyry had altered to clay.

Since this undiscovered dike was at the railroad cut where all geologists have walked, evidently it was not easily recognizable until the quarry worked some distance into the hill. Many more such dikes may exist. The rock of the dike has been less resistant than the quartzite, so that rotting and erosion have made a depression at the surface where it outcrops and the depression is filled with soil and covered by vegetation. Any other dikes would be likewise obscured. The quartzite also graduates from very hard to softer or "sandstone" areas, and these at the surface correspond with erosional depressions. To this the apparent terracing of the hillside is due (*10*, page 21). The many similar depressions may conceal also a few dikes.

Both the faulting and the erosion of the quartzite are difficult to rightly interpret without explanation of the phenomena of rock alteration. I take the view that the entire mass of rock now remaining at Redstone was once all vitrified, and the induration of sandstone to quartzite preceded the intrusion of lava now represented by the dike. Displacement then followed or in part preceded the intrusion. In the geologic ages since that time, the percolation of water down the joints has redissolved the cement, making "sandstone" patches and strata again. This view is not in accord with that expressed by Irving and Van Hise, who say (7, page 34):

"At Redstone the transition from argillaceous, reddish sandstone to completely vitrified, brick red to purple quartzite are frequent and abrupt. In places over considerable areas the appearance is as if the rock at higher levels had been vitrified by exposure. But in the railway cutting it is seen that the vitreous quartzites are not restricted to the exposed portions, but are interstratified with, and arranged in irregular areas in, an entirely unindurated crumbling sandstone. The peculiarly irregular distribution of the induration and the abrupt transitions from indurated to non-indurated material suggest the possibility of its production by descent along joints and spreading thence through the layers of a silica-bearing solution."

In the quarry certain shallow erosional depressions on the surface of the rock overlie patches of sandstone within the flinty quartzite. The patches are kettle-shaped, two or more times as deep as wide. Other soft patches extend on either side of joints. The dike just mentioned, besides being itself altered to clay for 20 feet (as far as it is seen), is in contact with leached walls. The foot wall for 4 feet is light-colored, becoming then red. The hanging or east wall is soft, sandy, light-colored rock for 6 inches next to the fault line, and then 2 feet of light quartzite are followed by the normal read. In the neary-by railroad cut the jointing and the leaching of the rock are seen to follow the stratification largely. In texture the quartzite consists of crystalline sand grains which are enlarged, either interlocking or with interspaces filled by silica, which may be partly amorphous. The sandstone phase has also secondarily enlarged grains, lacking the cement. The sandstone may be the quartzite with the cement redissolved—that is, with the last deposited mineral first removed again by leaching. Again: "there seems to have been a cutting down of the original grains and the formation of a cryptocrystalline groundmass inclosing scattered and corroded grains of quartz" (*10*, page 22). Hall (place cited) attributes this corrosion of the sand grains to downward circulation of water, though he appears to hold as nearly as was practicable the same view as Irving and Van Hise regarding the induration of the rock, for he says: "The silica thus dissolved and removed has doubtless acted as the indurating material for the underlying layers." The evidence of the deeply rotted volcanic dike in the quartzite argues that the leaching of the rock is vastly greater than has been realized heretofore. The induration also was originally general and deep, and the "sandstone" represents disintegrated rather than non-indurated rock.

By reason of the leaching and erosion as described, any original minor faults as well as dikes would tend to be concealed at the surface of the exposures. In the southern portion of the area, which is the more inclined and disturbed, the greater leaching and erosion has taken place, so that the lower strata appear there. Very evidently the hill of quartzite stands as it does because of the extreme resistance which the massive quartzite offers to erosion and weathering, and the relation of the Courtland quartzite to other rock formations should be interpreted accordingly. Some consideration may be given also to the fact that the lower strata are in part argillaceous, while the higher ones are rather uniformly pure and coarse-grained, becoming pebble-bearing or conglomeratic in certain of the strata.

The extension of the Courtland quartzite to the northeastward is indicated, as C. W. Hall says (*10*, page 23), by boulders strewn in the glacial

drift 4 to 6 miles from Redstone. The formation at Redstone appears to continue in force, under the glacial drift, in that direction. To the west it seems to end abruptly, since the granite rises in place of it in the Big Cottonwood valley, as already described. The total thickness of the formation is not known. The estimated 300 feet of strata in the exposed portion may be too little or possibly too great an estimate. Concealed faulting may decrease the apparent thickness or possibly increase it. Likewise the extent of this formation between the lowest exposed stratum and the granitic rocks beneath it is uncertain, because the amount of downthrow which the quartzite has suffered in relation to the granitics, seen westward of it, is unknown. The resistance of the quartzite to degradation from surface exposure is strikingly greater than that of granite, and therefore the relatively lower outcrops of the granitic rocks is not good evidence that they were not once as high or higher than the quartzite at Redstone. Since the extent of the original dislocation is unknown, the depth to granite under the quartzite is uncertain and, moreover, the existence of other geologic formations between them is possibly to be expected. Although it has been assumed by geologists that the quartzite at Redstone rested on the granitic rocks because these appear close below the New Ulm conglomerate quartzite, which was supposed to be the basal beds of the Courtland quartzite, yet there is reason for thinking to the contrary. That conglomerate is of Middle Cambrian rather than of the "pre-Cambrian."

The New Ulm basal Conglomerate: Cambrian

The quartzite conglomerate which outcrops on the left side of the Minnesota river, opposite New Ulm, a mile and a half above Redstone, has been heretofore considered by geologists as the basal part of the Courtland quartzite. It lies closely over the granitic rock; its strata dip 10 to 15 degrees, as if dislocated; it is a quartzite, and the contained pebbles, as reported, were all from formations older than the Courtland quartzite, whence the conclusion was easily drawn that it represents the basal part of the quartzite as seen at Redstone. In speaking of the contained pebbles in this conglomerate, Upham says (*6*, volume 2, page 159): "Neither the granite that outcrops close at the west nor the quartzite that occurs on a large area 1½ to 3 miles distant toward the southeast seems to be represented." C. W. Hall (*10*, page 23) makes essentially the same statement, and N. H. Winchell (*9*, page 156) says: "Probably there is no one who would call in question that this conglomerate and quartzite (that is, Courtland quartzite) are earlier than the Keweenawan eruptive age."

In company with Benedict Juni, I examined the ledges of the New Ulm

conglomerate somewhat closely, and found pebbles of quartzite and even of quartzite conglomerate like the rock which is *in situ* at Redstone. By this criterion, the New Ulm conglomerate quartzite is later than the Courtland quartzite and may be of Cambrian age. Further, the fact that this conglomerate is indurated is not evidence that it is Huronian or that it is not Cambrian. Quartzite masses are not uncommon in neighboring sandstones; for example, in the Jordan sandstone on the Blue Earth river, and in the Shakopee formation at Mankato, and therefore an indurated conglomerate of Cambrian age is not anomalous. The dip of the beds in such a coarse, thickly packed, unassorted conglomerate may well be that of original cross-bedding, and the close relation or evident contact with the granitic rock is in accord with the known unconformability of the Middle Cambrian upon older rocks in Minnesota.

In regard to the contained pebbles, those of quartz and of jasper or taconite are very abundant, while those of fine-grained gneiss are few and those of quartzite are rare. The quartz may be considered as mainly derived from Minnesota Valley granites, and the quartzite from the Courtland quartzite, while the gneiss and jasper are from formations not seen, though probably existing in this region. Numerically considered, the quartz pebbles are most numerous and the granitic rocks are immediately near; the quartz pebbles are rarest, and the rock *in situ* is seen a mile away. Accordingly the schist and "taconite" and jasper may reasonably be derived from an intermediate distance. Many of the jasper and quartz pebbles of small size may be secondary from the Courtland quartzite. A single pebble of what appears to be an altered red granite and one of medium-grained, light-colored gneiss were collected. The absence of pebbles of the unweathered red gneissoid or granitic rock which is now exposed 150 paces west of the conglomerate may indicate simply that there was no outcrop of unaltered rock of that type there at that time in position to afford pebbles for this conglomerate. The conglomerate is not uniform in composition. For example, quartzite pebbles are to be sought in the middle of the exposure. It may be noted also that the pebbles are of diverse sizes and more or less waterworn and rounded. Some are etched or pitted and nearly all are quartzose and such as an encroaching sea might have gathered from a deeply disintegrated rock surface.

The New Ulm conglomerate may rest on either a weathered or a fresh surface, as far as we know. It is exposed 50 feet thick in all and 20 feet in single vertical outcrop. It is jointed with the bedding and forms strata 1 to 6 feet thick. The dip of these beds varies between 10 and 15 degrees, and the strike changes somewhat in direction, but it is "roughly represented by the direction of the exposure being north 15 degrees east" (Hall, *10*, page 23 and plate III). The direction of the dip is at nearly

right angles to that of the Courtland quartzite at Redstone, but conforms in direction with that of the Cambrian and Ordovician beyond the Redstone quartzite mass. The latter is in seaward direction from the New Ulm basal conglomerate, and its present elevation and position are such as to indicate that in the Cambrian sea it must have stood as a high island or peninsula, and that the New Ulm conglomerate is or was continuous with the Cambrian basal conglomerate east of Redstone as at Minneopa falls.

At Minneopa falls, near Mankato, on the south side of the Minnesota River valley, a well was bored 1,000 feet deep.

"In boring, 575 feet from the surface a conglomerate was reached with pebbles of clear, fine, non-granular quartzite up to 2 or more inches in diameter. From this depth to more than 800 feet below the surface the borings consisted chiefly of quartzite pebbles indistinguishable in macroscopic and microscopic characters from the vitrified quartzite at Courtland. These pebbles are essentially different from those composing the 'basal conglomerate' beds opposite New Ulm" (Hall, *10*, pages 23-24).

I have examined, with Professor Hall's permission, pebbles from the Minneopa well and find that they have surface pitting and general characteristic form of the quartzite pebbles from the New Ulm conglomerate. If both are, as they now appear to be, parts of the same Cambrian basal conglomerate, then the difference in the prevailing rock constituent of the pebbles is a local one, indicating that the rock types, as seen in the outcrop of the New Ulm conglomerate quartzite, are of local derivation.

The geologic formations which appear in the Minneopa well are traceable toward New Ulm. The Jordan sandstone disappears from over the Saint Lawrence shales before reaching Judson, at which place the latter outcrops for 1 or 2 miles. Beyond Judson a lower sandstone rises into view along the railway, but is not seen beyond Cambria. The Cretaceous shales appear between Cambria and New Ulm, showing that the Cambrian had been deeply eroded on the south of the Redstone after Cambrian time, since the Cretaceous lies doubtlessly in unconformity in its place.

The Big Cottonwood Formation: Cretaceous

Shales and sandstones of Cretaceous age have been heretofore recognized in isolated outcroppings on the Big Cottonwood river and in neighboring parts of the Minnesota valley. Fossil leaves from certain sandstone strata have been described by Lesquereux (*4* and *8*), and from evidence afforded by these fossil plants he referred the formation to the Dakota group. Certain green shales which were supposed to lie higher than the fossiliferous sandstone, have been referred to the Niobrara group by Winchell and Upham (*6*, volume 1, page 576; volume 2, page 165).

In fact, the leaf-bearing sandstone is not under the green shales, but is quite the reverse. No such wide distinction as Dakota formation and Niobrara (that is, Colorado formation) is at all applicable, and not even a division into lower and upper formation is well defined. All strata are fresh-water deposits and are referable to the Dakota formation, although they possibly are contemporaneous with the marine Colorado formation or Niobrara. The name Big Cottonwood formation or beds will be useful in distinguishing this part of the Cretaceous in the region here described.

This formation extends continuously for 7 miles in the valley of the Big Cottonwood river, and is evident as far west as Springfield. From the Big Cottonwood valley it extends up the Minnesota to New Ulm and down the valley toward Cambria. It lies on three sides of the Redstone quartzite. The formation probably runs continuously westward toward Marshall, Minnesota, while it is cut off to the northeast and south, forming thus an area 20 miles or more long and 10 miles or less wide. It represents a river delta or filled valley of a stream which originally descended from east to west, as is shown in the cross-bedding in the strata. The Big Cottonwood formation now dips from west to east at about the same rate as the gradient of the Big Cottonwood river, the formation having been tilted.

The Big Cottonwood formation comprises coarse, clean sandstone and fine conglomerate, shales, potters' clay, limestone, and lignite. Alternate strata of almost any two kinds of materials may be seen locally. Owing to the prevailing and often very strong cross-bedding, no two exposures afford the same succession of strata. The color is red, green, white, yellow, blue, or brown. The deposit is clearly that of a river. Coarse, clean white or yellow sand occurs, in which there are seams of fine, tough, blue clay cross-bedding the sands at an angle of 10 degrees or less, and the sand frequently contains pieces of lignite, besides occasionally imprints of leaves.

There is no uniform division into upper and lower parts, but in general there are some differences between the lower and upper deposits. Limestone, which occurs at one end of the field, is in general median in position. It is found more particularly in the vicinity of the Redstone. The top of the formation is generally clean sand with clay seams or beds, which occur irregularly, but yet so that 40 feet of strata comprise 10 feet or less of clay, either in seams from a quarter of an inch to 1 foot thick or in several instances in a single thick bed. Below that there is red and green shale, sandy shale, clay, and some clean white sand, in strata which are 1 to 10 feet thick, but run unevenly. The lower part of the formation is 0 to 200 feet thick, as far as known, varying with the depth to subjacent rock, and comprises on the whole the greater part of the formation.

Pieces of carbonized wood and leaves occur quite generally in the upper or sandy part of the formation, and in a few places very good fossil leaves were collected. Brown, soft sandstone and ferruginous concretions of very local and limited development contain the leaves. At the north side of the river, in the southeast corner of section 34, Milford, Brown county, is where the specimens described by Lesquereux (*8*) were found. I have collected also in the northwest 1/4 of northeast 1/4, section 36, Milford, and in the center of section 31, New Ulm. At the south end of the Minneapolis and Saint Louis railway bridge over the Big Cottonwood many good specimens were found. This is the very top of the formation, while the other localities are variously in lower position. The last-named locality is evidently where James Hall collected leaves which Lesquereux later identified. At this place a species of Pelecypod was also found by Mr Juni. Pieces of wood occur in lower strata and even in the limestone. In the limestone at Heimann's limekiln and at Winkelmann's there are undescribed Algal secretions, similar to the Schizothrix, which builds lime in the lakes of Minnesota in recent time. The fossil Algal skeletons appear as nodules made up internally of laminæ of granular lime, with open, clay-filled, or calcite-filled intervals between them.

A description of the Big Cottonwood formation from place to place would be very much detailed, owing to the many changes and exceptions to any rule which might be given, but a few places are instructive. In one place on the Big Cottonwood river (northwest 1/4 of northeast 1/4, section 36, Milford), where the rotted granite, as before described, rises 10 to 15 feet above the river, about 40 feet of sand belonging to the Big Cottonwood formation is seen between the granite and the glacial drift. In other places along the river the formation is thicker by reason of the surface of the granite being lower. There is generally 50 feet of strata above the river level. At New Ulm the top is at about 870 feet above tide—that is, 75 feet or less above the river at high water—and the formation is over 200 feet thick. At Redstone village the strata of limestone and shales are in contact with the Courtland quartzite. The same strata extend thence under the meadow land to the small creek which passes Heimann's limekiln and some distance toward, if not to, the New Ulm quartzite conglomerate. From the creek eastward along the wagon road up the hill, shales and clay are evident to the height of about 875 feet above tide. A complete section is not shown distinctly here, but from the bottom of the creek to the top of the section there appears to be (*a*) limestone, 2 feet; (*b*) clay, 20 feet; (*c*) limestone, 2 feet; (*d*) shale mixed with limestone, 15 feet; (*e*) clay, 20 feet; (*f*) limestone, 1 foot; (*g*) clay or shale, 20 feet. Sandstone is not seen. The limestone is "nodular" or "concretionary," consisting largely of lumpy Algal secre-

tions from an inch to a foot in diameter and infiltrated with calcite. The lower limestones are largely "nodular," while those 20 and 40 feet higher up are more granular, laminated sedimentary deposit. The Algal limestone and the dominance of clay indicate that the area north of the Redstone quartzite, between it and the quartzite conglomerate ledge, was occupied by quiet water—a lake, in short. The lower limestones are represented, in their "nodular" form, on the west side of the Minnesota river south of Redstone, at Winkelmann's limekiln, and, again, as far as at the mouth of Kalb creek, there are thin sedimentary limestones and shales with flakes of lime in them, in a zone comprising 5 feet of strata. Traces of lime flakes occur 2 to 3 miles farther west.

Coarse sands with pebble-bearing strata are known only on the south of Redstone hill, and very evidently a river flowed by that course from east to west. This pebble-bearing sand occurs some 20 to 40 feet below the top of the formation, along the Big Cottonwood river, at the mouth of Kalb creek. The characteristically bright polished quartz pebbles appear also at New Ulm. This sand is known on the northeast side of the Minnesota River valley for several miles east of Redstone (in sections 16 and 20, Courtland, Nicollet county). The formation there appears to extend eastward, under the glacial drift. Two to 3 miles southeast and south of these last outcrops, Cambrian formations appear, rising to the same height and in place of the Cretaceous strata. The contact of Cretaceous and Cambrian I have not found, but doubtless the former lies here in an old valley, the south wall of which is of Cambrian rocks. Limestone is known on the south side of the Redstone close to the shelter of that rock, which formed locally the north wall of the Cretaceous valley. Shales should be expected to underlie the pebble-bearing sand, and they have in fact been traced on the right side of the Minnesota for 3 miles below the Big Cottonwood river. The coarse sand deposit is above sands and shales, indicating that stronger current followed as the Cretaceous valley filled.

In regard to the surface on which the Big Cottonwood formation rests, the evidence indicates a preexisting valley—practically a pre-Cretaceous valley. Since the strata rise to only half the height of the Redstone quartzite, or some 80 feet above the Minnesota river, the top of that rock may be supposed to have been exposed above the Cretaceous at all stages. The rotting of the dike, as described, and the leaching of the Courtland quartzite are evidently pre-Cretaceous in main. The granite outcrop on the Big Cottonwood river is rotted at least 30 feet and possibly 100 feet, and this would indicate that it had been a hill for ages before the Big Cottonwood formation of the Cretaceous began to surround it. The granite floor, as found in wells at New Ulm, is 300 feet below the top of

Redstone and 200 feet lower than the granite outcrop on the Big Cottonwood, thus proving a considerable valley to lie buried here.

From the direction of the cross-bedding in the sands, as already described, the river is shown to have filled the valley just mentioned from east to west, and the original valley may also run east to west. I have searched for evidence of this valley and the Big Cottonwood formation along the Minnesota river below Mankato, Minnesota, and along the Blue Earth and Le Seur rivers, which together make a north-to-south section crossing the line which the valley and formation must have followed if they extended that far. The clays and sandstones which are to be seen there, and which N. H. Winchell and Warren Upham described as Cretaceous, are in fact only the rotted or residuary portions of Paleozoic sedimentary rocks in main. In places, 20 feet of clay occur with stratification partially preserved and with quartz geodes, silicified oolite, fossils, and other marks showing the original rock to have been the Oneota and Skakopee dolomites; or, again, the same clay extends into depressions, or vertically into the dolomite as seams, or it fills "potholes," which same are leached and enlarged joints. Occasionally the leaching has made residuary clay in horizontal joints likewise. Original beds and strata of sand remain in the red clay. Such materials correspond to the rotted granite under the Big Cottonwood formation, and not to that formation. These residuary materials occur between 800 and 875 feet above tide, the main preserved part lying at 825 to 850 feet. On the Le Seur river (north line of section 2, town of Rapidan, Blue Earth county) there are 12 feet of clean gravel of finely polished siliceous pebbles, an inch or less in diameter, some of which are the remnants of Silurian and Devonian fossils. This rests on coarse sand 20 feet thick over the Jordan sandstone. The top of it is about 840 feet above tide. This gravel and sand correlates evidently with the Big Cottonwood formation, but it lies in a shallow valley, as the section along the river indicates. The cross-bedding in the gravel is from east to west. At one place a small pocket or lens of fireclay was formerly discovered over the gravel. It has now been mined out.

The evidence of the leached rock floor and the Cretaceous sand and gravels along the Le Seur and Blue Earth rivers, and of the residuary clays in the Oneota dolomite near Mankato, Kasota, and Ottawa, along the Minnesota river, indicates that the general surface of the old land along that section lies now between 850 and 900 feet above tide and was originally high above the Big Cottonwood formation. From such a land area the red and blue shales, white sands, polished siliceous pebbles, and that which is now blue clay could have been derived. Between Kasota and Ottawa, and especially north of Ottawa, the rock wall is missing along the present Minnesota valley and possibly a pre-Cretaceous course, and

the Big Cottonwood formation passes the river at that place in a general easterly direction from New Ulm. By reason of dip, the Cretaceous would lie below the river.

North of the Big Cottonwood the glacial drift is sufficiently intact to leave the question of former and present relation of the Cretaceous rocks greatly obscured. But, in the valley of the Minnesota river, the drift appears to extend down in place of the Cretaceous, from north of New Ulm, 10 miles to a place (some 6 miles north from the Big Cottonwood valley) where fresh granitic rock rises 25 feet above the river. Evidently both the Cretaceous rocks and the Archean granites have been greatly eroded there in post-Cretaceous, pre-Glacial time, and apparently a drift-filled valley crosses the course of the Minnesota river. At Sleepy Eye, which is north of the Big Cottonwood river, the granitic rock is said to be found in a well at a depth of about 200 feet—that is, at 800 feet above tide—no Cretaceous intervening between it and the drift. Absence of rotted granitic rock argues post-Cretaceous erosion.

Glacial Drift and River Deposits: Quaternary

Character of the Drift

The drift in the region about Redstone is mostly of boulder clay or till, although modified drift—gravel and sand—regularly accompanies the till. All the older rock formations of the region were doubtless once covered by glacial drift, as they are yet, excepting in the river valleys.

The surface of the drift outside of the river valleys is marked by irregular hills and closed basins, such as are characteristic of the glacial drift of the Wisconsin stage, but these irregularities occur with such monotony as to give the country the aspect of a nearly level land, sloping gently toward the Minnesota river. Two or 3 miles from the river the average altitude of the land surface is at or above 1,000 feet above tide, while along the border of the Minnesota valley few points only reach to 1,000 feet. One such point within the city limits of New Ulm is 1,015 feet.

The drift averages about 200 feet thick, but is far from uniform, because of the surface irregularities and the unevenness of the rock base upon which it rests. Redstone hill has the highest known rock subjacent to the drift. There the Courtland quartzite formation has been covered about 50 feet by till. The Big Cottonwood formation was covered from 100 to 150 feet deep. Northwest of New Ulm the drift appears to extend to or below the river level, or 200 feet deep. The Big Cottonwood river cuts through the drift into the Cretaceous rocks for at least 7 miles above its mouth and probably all the way from Springfield, the till and associated gravel beds being 100 to 150 feet thick, as seen in the bluffs.

There are two distinguishable drift sheets in this region, the same as have been generally recognized by Minnesota geologists (see Upham, *6*, volume 1, page 580). These are the Wisconsin and probably the Kansan, as recognized in Iowa. They are best called Old and Young glacial drift, I think, for the present purpose. The Old glacial drift fills, as described, over an uneven surface, but presents apparently a rather uniform upper surface of its own, in general sloping from west to east. On the northeast side of the Minnesota river the top of this Old drift is at about 890 feet above tide. The Redstone hill therefore stood above the surface of the Old drift, and it was probably on the west side of a wide shallow valley. On the Big Cottonwood river, 5 miles west of Redstone, the Old till rises to about 975 feet above tide. There is, as far as seen, a bed of fine, assorted and stratified, ferruginous, often cemented gravel, at the base of the Old drift. In one place, just above the mouth of Kalb creek, a small pre-Glacial channel, filled with a thin layer of till under strata of peat and clay with logs of wood, lies beneath the basal gravel bed. Such wood is found also in wells in the central high part of New Ulm city. A few lenses of fresh gravel occur also scattered in the till of the Old drift. While the Old till is dark and compact, as a rule, it is locally leaching to reddish gray color at surface exposures and along water-bearing gravels.

On the Old drift rests the Young drift, with its rolling upper surface. It has a gravel bed at its base, as a rule, and other sand or gravel patches at the top. Of the two till sheets, the lower contains fresh Cretaceous sand and clay patches occasionally, besides lignite. The upper contains many pieces of a different lignite and has other differences—lighter color, looser texture, etcetera—but it consists so largely of materials of the Old till as to be distinguishable mainly by its superposition. The Young drift is 10 to 100 feet thick.

Besides the Old and Young glacial drift, there are terrace deposits of gravel, sand, and clay in the river valleys. These deposits have come mainly out of the glacial drift and are, moreover, very closely associated with the same. They are found sometimes in confused relation with them. They were formed, moreover, during the time when the glaciers were yet retreating from the country, and technically they belong to the Glacial or Pleistocene period of the Quaternary age. In the Minnesota valley the terraces were made obviously by the great river Warren, which formed the outlet to the Glacial lake Agassiz, between the time of retreat of the ice from this region and its disappearance from the north.

THE MINNESOTA RIVER VALLEY

The Minnesota river for many miles above New Ulm has a direct, simple trough-shaped valley, with steep sides 200 feet high and with broad

bottom a mile wide. This is the channel of the glacial Minnesota or "river Warren," where that river eroded into the glacial drift. At New Ulm the valley widens over the top and a system of terraces appears. The river Warren was also once divided here by an island which is now the site of the city of New Ulm (*6*, volume 1, page 582). At this place the valley is cut not only in the glacial drift, but also into the Big Cottonwood formation. At Redstone, 4 miles below New Ulm, the river Warren encountered the mass of Courtland quartzite, and this obstruction caused the river to widen its valley and build terraces even several miles above the obstruction. The terraces at New Ulm correlate largely with the stages of the valley's making at Redstone.

From the direction of the valley as it now lies at Redstone, it is readily seen that the river Warren flowed first directly across the present area of Courtland quartzite. At that early stage the river had only glacial drift to encounter, but after cutting its valley to a small depth the quartzite was met. This rock was highest on the left, and, being very resistant, it swerved the river gradually to its right side, and finally entirely beyond the west end of the quartzite formation. As the valley was gradually cut down, Redstone hill was thus uncovered and left extending half a mile out into the valley.

The making of terraces by the river might be attributed to three factors, namely, variation in flow of the stream, inequality in the quartzite barrier, and inequality of the other formations across which the river was diverted. Of these the first may be set aside, since elsewhere, especially above New Ulm, the valley indicates rather a constant stream. The relation of the stream and quartzite appears also to have been rather a uniform one. On the highest and earliest uncovered part of the quartzite its surface bears prior glacial striæ (*6*, volume 2, page 165; *10*, page 21), thus proving that the river scarcely cut the quartzite there; also, at lower levels, not much of the quartzite was removed. The surface there is in fact grooved, furrowed, and worn into irregular knobs and depressions, in the direction and manner of rapid stream erosion, by the river Warren; but yet the cause of this appearance of great erosion is that the leached and softened portions of the quartzite, as before described, was alone worn away. The firm quartzite appears thoroughly polished and generally rounded, but was in fact so little cut away that much, if not the greater part, of the softened or superficially leached rock was protected by it. While Redstone hill appears at first sight to have been worn into a rugged remnant by the river Warren, there is still better reason for thinking that the hill was practically an impregnable barrier to the stream. The course of the valley around the base of the hill is further evidence to this effect. The present form of the hill is therefore nearly

its earlier one. Nothing appears, therefore, in erosion of the hill to produce terraces in the valley, and nothing also in the form of the hill to produce any other marked result than the swerving of the river Warren gradually to the right of it.

The making of the terraces may, however, be attributed to the third factor, namely, to that of unequally resistant geologic formations, which were cut into as the river evaded the Redstone quartzite. These evidently were the intact Cretaceous and Glacial deposits. Since the pre-Glacial drainage here ran, as before stated, north of the Courtland quartzite area and the inter-Glacial valley was on the east side of it, the post-Glacial valley which runs on the west side is therefore a new course, from New Ulm passing Redstone, and accordingly the geologic formations may be supposed to have been intact there when river Warren began its valley. Some portions of these formations are still found between Redstone hill and the river.

The formations which were eroded here by the river are the Young drift, the Old drift, and the Big Cottonwood formation, and each of these comprises hard and soft parts, such as to cause the erosion of a stream through them to progress by stages. The more resistant parts are (1) the boulder-clay of the Young drift, (2) that of the Old drift, (3) the tough clay beds at the top of the Big Cottonwood formation, and (4) the red shales at a lower horizon in the same. The river terraces correspond to the tops of these resistant parts, having formed by the erosion of the softer parts, namely, a loose gravel bed at the base of the Young drift, another at the base of the Old drift, and the thick beds of loose coarse sand below the top of the Big Cottonwood formation. Whenever the river cut down to one of these at one point before others, the deepened channel could be readily widened by lateral erosion of the softer bed and undermining of the harder ones, from which presumably resulted terraces bounded by steep scarps, such as are now seen.

The surface of the terraces show generally a gradient greater than that of the present river, and they are covered with coarse gravel, and they appear to be remnants of rapids and rapidly sloping channels passing Redstone. Yet the terraces, although largely detached or interrupted, show generally a correspondence one to the other much as terraces of subsidence do. Their correspondence may be due rather to the control of the eroded geologic formations than to gradient of the river.

On the right side of the valley the highest, or 940-foot, terrace, resting on Young drift, forms the site where the cemeteries are located, on the west of New Ulm. The 910-foot terrace, resting on Old drift, forms the high central part of New Ulm city. The 870-foot terrace is represented on the one side of the last by the abandoned channel back of the city

proper, and on the other side by the level along which the business streets extend. A triangular tract on which the Minneapolis and Saint Louis railway runs south of the Cottonwood river is of the same. This terrace rests on the top of the Big Cottonwood formation. The 830-foot terrace is occupied by the depots and railway tracks at New Ulm and is traversed by the railways, extending to the Big Cottonwood river and thence three miles beyond it, occupying a great part of the valley opposite Redstone hill. It rests on the red shale zone of the Cretaceous. These terraces are covered generally by a few feet of red loam over more or less gravel, both of which were made by the river Warren.

On the left side of the valley the 940-foot terrace runs nearly continuously from a mile above to four miles below the Redstone quartzite barrier (*6*, volume 2, page 173). The 910-foot terrace extends nearly a mile and the 830-foot terrace forms a broad meadow north of Redstone village. All these terraces in the valley passing the Redstone hill are in strong contrast to the simple valley above New Ulm.

THE BIG COTTONWOOD VALLEY

The valley of the Big Cottonwood river joins the Minnesota on the west side, opposite and a little above Redstone hill, just at the place where the river Warren was most diverted by that obstruction. Since the Big Cottonwood is tributary here, the cutting of its valley may be presumed to have proceeded *pari passu* with that of the Minnesota, and to have been influenced in somewhat the same way. The Big Cottonwood valley is a remarkably irregular one, as shown on the map (figure 1). It is nearly 200 feet deep, cut through the glacial drift and into the Cretaceous sands and shales; it has broad embayments, with terraces and steep sides. The river meanders from side to side in its valley and repeatedly undermines its bluffs, causing great landslides. Where the river encounters easily eroded sandrock the undermining is rapidly done, but where shales now appear at river level, the undermining is slow. The entire valley has been made in that same manner. The downward erosion has been accompanied by wide lateral erosion where soft rock was encountered by the river. The same succession of hard and soft formation is found along the Big Cottonwood as along the Minnesota valley at and below New Ulm, and since the two rivers cut down *pari passu* the terraces in the two valleys largely correlate.

While the Minnesota valley was made by a large, flood-like stream—the river Warren—and the modern stage of that river, the Minnesota, now meanders freely within it without conflict with the sides, the Big Cottonwood valley, on the contrary, has been made by a small river, as it now is,

at all stages of its making. An old high channel, representing an early stage of the river, is found crossing section 32, New Ulm. This channel is sharply defined and in size indicates a river like the present one. It is cut through the upper glacial drift only. Another such channel, in section 4, Milford, runs across to the mouth of Kalb creek, and thence a little south of and parallel to the present river's course. The part of this channel below Kalb creek cuts across even the 830-foot terrace, and therefore was followed by the creek as late as the modern stage of the Minnesota river; but that part above the creek was abandoned earlier.

The Big Cottonwood crosses the 830-foot terrace of the Minnesota valley, and it has there a narrow course, excepting above Kalb creek, where it meanders back against the bluff. At that place it made a wider way and evidently removed the larger part of what I call an 870-foot terrace, having intercepted Kalb creek. The narrow course or valley reveals the relation of the Big Cottonwood river to the Minnesota river in its modern stage. The earlier relation at the junction of the two valleys is not well shown by terraces, these having been cut away by the meanders of the Big Cottonwood. I am inclined to think, however, that there is a gravel-filled former channel of the Big Cottonwood river which runs through the 830-foot terrace from the mill in northeast direction to the Minnesota river and which was abandoned at a time when the 830-foot terrace still served as floodplain for the river Warren. The river has been a swift stream and heavily loaded with sediment at all stages, as it still is, and it could have cut and refilled a channel quickly.

Apparently the general effect of the tributary stream should be to crowd the river Warren and the Minnesota toward the opposite bluff—that is, against Redstone hill—by means of the loads of sand and gravel which must have been thrown into the side of the main valley.

Conclusion

From the foregoing descriptions it may be seen in particular that the Redstone quartzite, or that which now composes Redstone hill in the Minnesota valley, has stood with remarkably little change through many geologic ages. For the greater part of the time since the pre-Cambrian period its top has been exposed to destructive forces of the atmosphere. Its history may illustrate the many times greater power of resistance which a surface exposure of a quartzite mass may have over that of ordinary rock formations. Even the granite rocks and porphyry dike appear weak in comparison.

In pre-Cambrian time the quartzite was intruded and displaced, probably so as to lie lower than adjacent granitics, and then by the relatively

rapid weathering away of these it came to again stand as a prominence above them. In Cambrian time it was met by the advancing ocean, which, instead of demolishing it, flowed around it, leaving a shore deposit of gravel even on its landward side. For several geologic ages the Redstone quartzite then stood as a great rock above a neighboring valley, much the same as the Baraboo quartzite of Wisconsin now stands. During Cretaceous time the river valley passing its south side filled with delta deposits, but probably leaving the top of the Redstone quartzite exposed well above the sedimentation plain. During the Tertiary, land erosion again made a valley, which was some 200 feet deep, crossing the granitic area to the north of the Redstone hill. During Pleistocene or Quaternary time the top of the quartzite was twice crossed by great glaciers. From the glaciers the rock received slight grooves and striations which are still clearly seen. They bear south 33 degrees east. The glaciers also spread sheets of till over it, although in inter-Glacial and in post-Glacial time erosion in part at least bared it again.

Although the geologic formations are all of scientific interest and have been described in detail in the preceding pages, the Redstone quartzite stands out as the most prominent feature in the geology of the area here described.

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NEBRASKA "LOESS MAN"[1]

BY B. SHIMEK

(Read by title before the Society December 31, 1907)

CONTENTS

INTRODUCTION

The antiquity of man is a subject of such intense interest that any evidence which seems to suggest or offer proof of it receives widespread attention, especially if the evidence is of the kind which is termed scientific. Scientific evidence in cases of this kind is either somatological or geological.

Unfortunately in the limited number of examples of more or less ancient man which have been reported the somatological evidence appears not very satisfactory to the layman, because it is of necessity concerned with mere fragments or with such a limited number of individuals that general conclusions appear to be unsafe.

[1] Manuscript received by the Secretary of the Society July 24, 1908.

The geological evidence is also extremely unsatisfactory, because in the great majority of cases in which human remains have been found the first excavations were made by those not skilled in the interpretation of the superficial deposits to which such remains seem to be limited.

The flimsiness of much of this evidence is well illustrated by a recent paper,[2] in which in all seriousness the author quotes as evidence, "based on actual discoveries," Aughey's absolutely unreliable report of the discovery of such evidence in the loess of Nebraska; the discovery, by Thomas Belt, of a skull in "what was supposed to be the western extension of the loess in Colorado;" the finding of a "stone ax 70 feet beneath the surface in loess in Illinois"—a statement which is especially interesting because there is no known place in Illinois where the loess reaches even approximately that depth; Witter's cautious references to the discovery, by another party, of arrow-heads under extremely doubtful circumstances;[3] and Miss Owen's report of the discovery, at a depth of 4 feet, of a stone ax at Saint Joseph, Missouri, "supported by the legal affidavit of the foreman of the quarry," which was, judging from the description,[4] simply imbedded in a mound of comparatively recent human construction, of the type which is common along the bluffs of the Missouri valley.

In this account are also included as conclusive evidence the last two discoveries of this kind, the "Lansing man" and the "Nebraska loess man," to which unusual interest attaches because in both cases excavations and observations were made by men actively engaged in scientific work.

The case of the "Lansing man" has led to much controversy, which, however, was scarcely warranted, as the remains were found in a deposit clearly distinct from ordinary undisturbed loess,[5] evidently consisting of slumped material—a fact which leaves the question of age altogether problematic and certainly gives no assurance of great antiquity.

The "Nebraska loess man" bids fair to give rise to an equal amount of controversy, though as yet the conclusions of the discoverers have gone practically unchallenged, at least on the geological side, and have been quoted as decisive.[6]

Previous Work

The somatological evidence has been considered by Dr H. B. Ward,[7]

[2] N. H. Winchell: Records of the Past, vol. vi, May, 1907, pp. 148-157.

[3] See Proceedings of the Iowa Academy of Sciences, vol. i, part 2, pp. 66-68, 1892, and the American Geologist, vol. ix, 1892, pp. 276-277.

[4] See Winchell's paper, p. 154.

[5] See writer's discussion in Bulletin of the Laboratory of Natural History, State University of Iowa, vol. v, November, 1904, pp. 346-352.

[6] See Winchell, ibid., pp. 156-157.

[7] Nebraska Geological Survey, vol. ii, 1906, part 5, pp. 319-327. Putnam's Monthly, January, 1907, pp. 410-413.

who is of the opinion that the remains indicate a "primitive people," and Dr H. F. Osborn,[8] who concludes that "even if not of great antiquity, it is certainly of very primitive type and tends to increase rather than diminish the probability of the early advent of man in America."[9]

The geological evidence has thus far been presented only by Dr E. H. Barbour,[*] who definitely refers the deposit in which the human bones of the lower layer were found to "undisturbed loess."

Field Work

Professor Barbour's very positive assurance that the loess was undisturbed, caused the writer to make an especially careful investigation of the deposits shown in the Gilder Mound section before reaching a definite conclusion, and he accordingly made several visits to the Long hill locality and spent fully a week in the examination of the mound and its immediate surroundings. In addition to this, he has spent much time in the past twenty years in investigating the loess and glacial phenomena in the territory including this locality.

The first of the visits to the Gilder mound was in March, 1907, in the company of Doctor Barbour and Mr Gilder, and the writer is indebted to both gentlemen for much information concerning the details of their observations, which made possible the closer connection of the observed phenomena with the published accounts. The work was continued by the writer on the following day, but various misfortunes prevented its completion until the following summer, when two more visits, aggregating five days, were made.

Location of the Mound

Throughout the greater part of its extent in eastern Nebraska, the valley of the Missouri river is bordered by rounded and more or less interrupted bluffs, which are distinctly unlike the wind-whipped bluffs of the east, or Iowa, side. Northward from Omaha these bluffs recede from the river in a slightly crescent-shaped line for a distance of about 8 miles,

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[8] Century, vol. lxxiii, January, 1907, pp. 371-375.

[9] To these should be added the very complete paper by Dr Ales Hrdlicka in Bulletin no. 33, Bureau of American Ethnology, 1907, who concludes (page 98): "Referring particularly to the Nebraska 'loess man,' the mind searches in vain for solid ground on which to base an estimate of more than a modern antiquity for the Gilder mound specimens."

Doctor Hrdlicka's paper was received after the preparation of this discussion, and while it contains interesting evidence and conclusions bearing on other phases of the case, these are not here discussed, the writer deeming it more satisfactory for purposes of comparison to leave the present paper unchanged.

[*] See Bibliography.

and again return to it just above Florence. Northward from Florence the bluffs are again more sharply defined, and form a series of abrupt

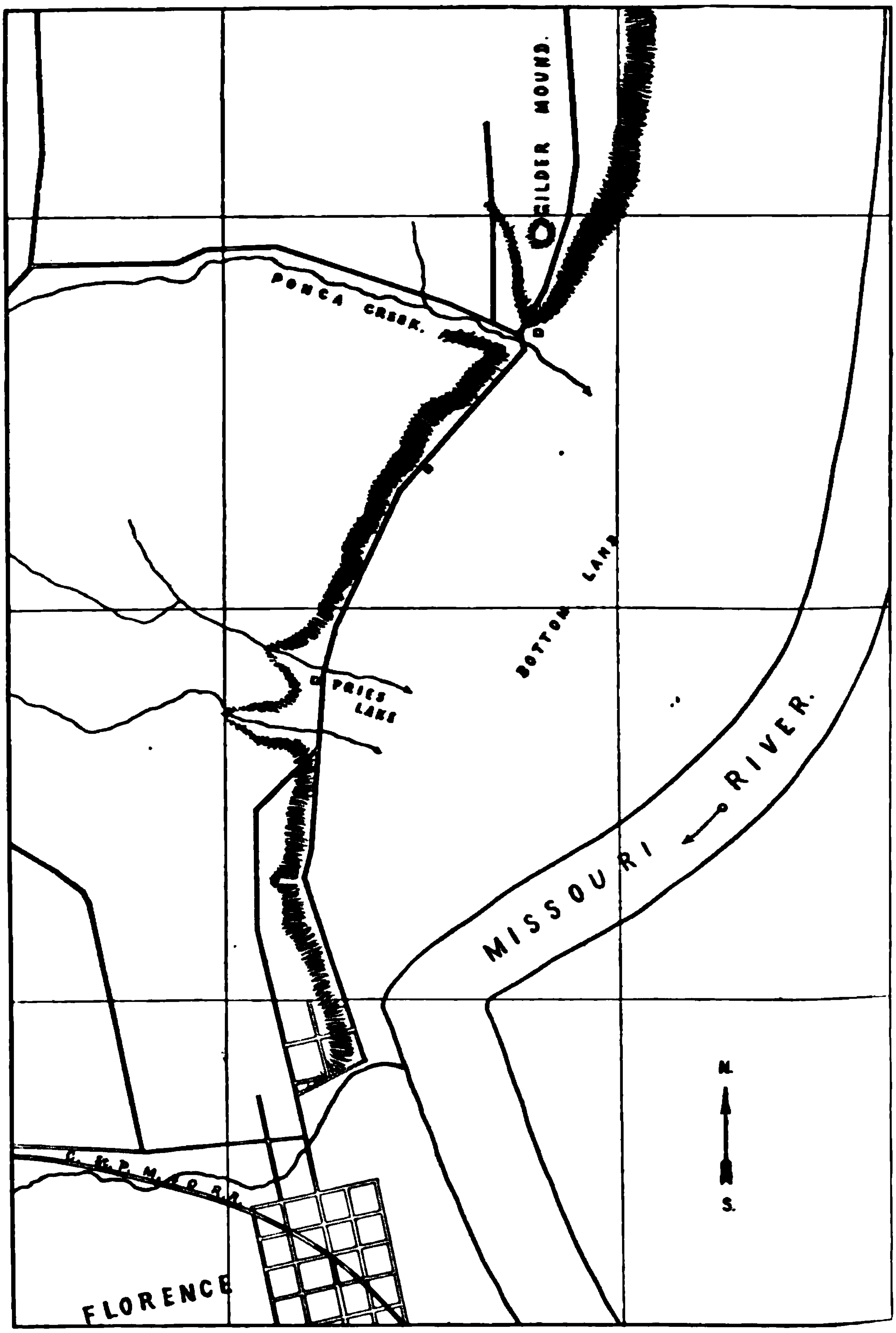

FIGURE 1.—*Map showing Location of Gilder Mound.*

headlands which are more or less broken by deep ravines (see plate 14, figure 1). The uplands of which these bluffs form the border extend westward for some distance, gradually running out into typical rolling

Kansan territory. The roughest parts are nearest to the bluffs, and are characterized by high rounded ridges the cores of which seem to consist largely of Kansan till and clays and which are capped by loess rarely, if ever, exceeding 35 feet in thickness. The bluffs between Florence and Ponca creek show more or less drift, capped with loess. The former rises to a height of 95 feet above the road north of Pries lake. The latter rarely reaches a thickness of 30 feet. It is fossiliferous at several points.

These ridges sometimes extend almost parallel with the river valley, and their abrupt eastern slopes then form the immediate river bluffs. On such a ridge, known as Long hill, located about 3 miles north of Florence, Nebraska (see figure 1), Mr Robert F. Gilder, of Omaha, discovered the mound containing the remains of the "Nebraska loess man."

This ridge is a spur extending southward from a more massive higher elevation (at its highest point fully 200 feet above the valley) and terminating just north of Ponca creek. The wagon road leading north from Florence follows the base of the main bluffs to Ponca creek, and then ascends the ridge, practically following the crest, which here lies close to the very abrupt eastern slope, to the summit of the spur. Gilder mound occupies the highest point on this spur, about 12 rods north of its southern base and 50 feet west of the road, which is here 10 feet lower than the mound. Its elevation above the road at the southern base of the ridge is 150 feet, and above low water in the Missouri river about 190 feet.

The mound itself was somewhat elevated above the surface of the ridge, having a slight slope even to the north, though the crest of the ridge slopes distinctly southward. It was covered with forest, the largest trees on or near the mound being bur oaks (8 to 12 inches in diameter), a walnut (10 inches), and a basswood (8 inches).

Its dimensions could not be accurately determined on account of the dense forest covering and the gradual blending of the surface of the mound with that of the ridge, but the lateral sections which were made show that the disturbed materials forming the mound extend beyond the limits of the excavated area.[10]

Previously Reported Position of Human Remains

In this mound the first explorations of Mr Gilder and Doctor Barbour revealed two distinct layers of human bones, the lower containing five skulls in a layer of "packed clay or loess" at a depth of 4 to 5 feet, and the upper three skulls and many bones of a more advanced man.

[10] For a more complete discussion of the extent of the mound, etcetera, see Robert F. Gilder's paper, "Recent excavations at Long's hill, Nebraska," in American Anthropologist, vol. 10, 1908, pp. 60-78.

In the lower stratum "several bones were deeply gnawed by rodents; one or more appear to have been hacked or scraped by some flint blade."[11]

"The three skulls buried intrusively were in a mixture of black soil and buff subsoil. The five primitive skulls and certain bones were fragmentary, water-worn, and scattered through four or more vertical feet of original undisturbed loess, and plainly belong to that formation."[12]

Later Barbour described the location of the bones as follows:[13]

"The upper two and a half feet of the mound is just such a mixture of black soil and buff subsoil as would naturally result from digging and burying. It is loess which has been disturbed. In this superficial layer were the three skulls of a later type, and adjoining them were numerous bones. Below this layer comes clearly defined bright buff undisturbed original loess, with its characteristic lithological structure, its lime nodules and shells; and through it to a carefully measured depth of seven and one-half feet are scattered bits of human bone. Here were found the five primitive skulls, each one being more or less fragmentary."

Still later the same writer says:[14]

"Here were found two mound-builder skulls, and below them parts of eight skulls and many bones of a still more primitive type. Two of the skulls are mound builders' in all probability. Together with them was the skull of a young child, differing from the others in color, texture, and thinness of skull wall. It is presumably that of a modern Indian. These were found in the upper layer, readily discernible as a mixture of black soil and light buff subsoil, such as would result from digging and burying. This layer has a thickness of two and a half feet. Below it was a distinct undisturbed layer of unmistakable loess, and in it to a depth of twelve feet were many fragments of human bones, loess shells, and stray angular pebbles."

He concludes that the bones "in the loess doubtless antedate the hill itself, while those in the upper layer are subsequent to it."

SECTION OF THE MOUND

THE EXCAVATION

The writer reexcavated the mound and the loess underlying it during each of his three visits and found only fragments of bones, but the strata in which they occurred were distinct. The last excavation extended downward until a depth of 14 feet was reached. A boring with a two and a half inch auger was then made to an additional depth of 17½ feet. The excavation was also successively extended eastward and northward,

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[11] Barbour: Nebraska Geological Survey, vol. II, p. 327.
[12] Ibid., pp. 326-327.
[13] Putnam's Monthly, January, 1907, p. 503.
[14] Nebraska Geological Survey, vol. II, pp. 333-335.

and a clean section (see plate 15, figure 1) was made each time. The combined result is here briefly stated:

Beginning at the surface and going downward, the section presented the following succession:

1. DARK SURFACE SOIL

The uppermost layer, nearly 3 feet in thickness, in which the more recent remains were found, consists of dark, loose soil near the surface, but from 1 to 2 feet below the surface the material is yellowish, somewhat loess-like, as though loess had been heaped up in the more recent burial. The uppermost black soil was subsequently discolored by the abundant forest vegetation.

2. LIGHTER LOESS-LIKE SUBSOIL

The uppermost layer shades below into a lighter brownish material, which is loose and contains numerous small irregular nodules of calcium carbonate and many roots. This layer extends from 3 to 7½ feet below the surface, and in this, at a depth of about 6 feet from the surface, were found the older human remains. Here the writer also found fragments of bones, a granite pebble, several flint chips, fragments of *Polygyra* and of a fresh-water mussel, the latter wholly unidentifiable, but suggesting *Unio pressus* or an *Anodonta,* forms now found in the rivers of this part of Nebraska. Professor Barbour refers to this layer in most positive terms as "original undisturbed loess," but the loose texture, very numerous small nodules, and very abundant roots all suggest a comparatively recently disturbed soil into which the pebble, the flint chips, and the fragments of mussel shell found their way intrusively with the human remains. No such combination of materials is known in clearly undisturbed loess in this country and none has been found excepting in connection with mounds which are clearly the comparatively recent work of man.

It is possible that even the land shells, *Polygyra* and *Succinea ovalis* (not *avara,* as reported by Professor Barbour), were introduced into this part of the section in the same way, for they are even now living, with several other species of land shells, on the surface of the ridge from its summit to the base.

A comparison of the material was also made with the section shown along the road from near the base of Long hill to a point 50 feet east of Gilder mound, and the difference is marked. This section[15] is fully 10 feet deep at a few points, and while its upper 3 to 6 feet show a very slight brownish discoloration, such as is not uncommon in this territory where there has evidently been a long-persisting forest covering, yet in the

[15] Figure 2, plate 14, shows the middle portion of the road-cut.

more compact texture, fewer nodules and roots, and total absence of pebbles, flint chips, and fragments of mussel shells, to say nothing of human bones, the material differs unquestionably from that found in the pit. The latter is certainly not undisturbed loess.

3. BURIED SOIL

Additional convincing evidence of the correctness of the foregoing conclusion is furnished by the third layer, lying at a depth of 7½ to 8½ feet below the surface and blending with the layers above and below. This is shown as a dark band between the six markers in figure 1, plate 15. It is a band of loose dark material, much like the topmost soil, and it is evidently a buried soil. In it the writer found a flint chip and a few shells of *Succinea ovalis*. This band is approximately at a level with the top of the bank at the road 50 feet east. Its depth, 7½ to 8½ feet, is not unusual for ordinary mounds. It is evident that the base of this band marks the downward limit of the disturbance of the soil in the earlier sepulture.

Professor Barbour evidently attached much importance to the presence of the lime nodules as characteristic of loess, but as a matter of fact they are often found in drift and other loose deposits and the writer has seen them fully an inch in diameter clustering about *living* roots in loess!

4. TYPICAL LOESS

Below the buried soil lies typical loess, its uppermost 2 feet somewhat discolored, as if it had once served as a subsoil or as if the change in color was due to percolation from above. The lower limit of this discolored band is shown by the single marker in plate 15, figure 1. This loess is close-grained, easily cut through, compact, yellow, with bluish gray lines and streaks, especially in its lower part, fossiliferous, with occasional iron tubules, and showing the characteristic laminated structure when broken vertically. Unlike the upper disturbed layer it contains few but larger and round nodules of calcium carbonate. The shells are all terrestrial and are chiefly *Succinea ovalis.*

The boring in the bottom of the pit revealed the same structure to a depth of nearly 31½ feet from the surface, the last few inches being harder and more mucky, suggesting that the base of the loess is not far below. A lack of tubing prevented deeper boring.

Professor Barbour reports the finding of scattered fragments of bone even in this layer to a depth of 11½ or 12 feet, but the writer failed to find any such fragments after many hours of careful search and digging, in which he was assisted by Mr L. Buresh, a student of the Omaha High School. There were a few flat chip-like lime nodules, apparently formed

FIGURE 1.—BLUFFS BETWEEN FLORENCE AND LONG HILL

The latter is just visible at the extreme right. Looking north

FIGURE 2.—CUT ALONG ROAD ON LONG HILL, ABOUT HALF WAY BETWEEN THE BASE AND GILDER MOUND

Shows loess only all the way up. Looking north

BLUFFS NEAR FLORENCE, NEBRASKA AND CUT ON LONG HILL

Figure 1.—The buried Soil (between the 6 markers) in Gilder Mound

Figure 2.—A Gopher's Hole in Loess, extending 7 feet below the Surface, Waverly, Iowa

SECTION OF GILDER MOUND AND LOESS AT WAVERLY IOWA

along some of the deeper seated roots, but not a trace of bone was discovered in this layer.

Possible Mode of Intrusion of Bone Fragments into true Loess

Fragments like those found by Professor Barbour certainly are not widespread or common, and, if clearly coming from the loess layer, were probably carried down through the numerous tubes, or canals, some of which were undoubtedly formed by the decay of roots, and others probably by burrowing mammals, such as gophers. At a depth of 9½ feet such a canal was found filled with dark, loose soil-like material, evidently from one of the upper layers. At 10 feet a tube 2½ inches in diameter contained a very little decayed root material and was partly filled with loose yellow loess. At a depth of nearly 11 feet a large tube, probably a gopher hole, was traced obliquely for several feet. It was partly filled with light and loose material, dark-colored only in places. At 12 feet a root cavity 2 inches in diameter was partly filled with decayed root material and partly clean and open, without a trace of organic discoloration.

Fresh, living roots were found to a depth of from 11 to 12 feet.

All of these cavities were in otherwise undisturbed loess and could be traced in part, or others similar to them could be found, in the looser layers above. Small bone chips could easily have been carried down either by water or by animals from the burial level. The section of a gopher hole in freshly excavated loess, shown in plate 15, figure 2, demonstrates that such excavations occur elsewhere in the loess.

Burial Habits of Mound Builders

THE LAKE OKOBOJI MOUND

Professor Barbour also lays great stress on the fact that the bones of the lower layer were scattered, "water-worn," and in part gnawed by animals. The writer confesses a lack of experience with material of that kind, but the report of an experienced anthropologist, Dr D. J. H. Ward, formerly of Iowa City, but now of Colorado, upon a similar case may be of interest in this connection.

Doctor Ward explored a mound near lake Okoboji, Iowa, containing numerous human remains. In his report[16] he discusses *three* distinct types of skulls and skeletons—one found at a depth of 6 feet, another at a depth of about 4 feet, and a third at a depth of less than 2 feet, all in the same mound. He says:

"We have evidence of perhaps six different orders of burials. The bones buried at the bottom were not buried with the flesh on them. Evidence points

[16] Proceedings of the Iowa Anthropological Association, vol. ii, 1905, pp. 14, 15.

to the fact that these men were killed elsewhere and that their bones were brought home and placed in a bundle in what was then a small pocket dug beneath the floor of the hill. Among the proofs that these remains were not buried with their flesh are scores of marks made by the teeth of wolves or other animals while gnawing the flesh. Again, the absence of small bones is an indication of this fact. In the case of one skull some of these small bones had been preserved and brought home by using the skull as a basket. While preparing it, ten bones from various portions of the body rattled out."

This quotation is of special interest because it suggests certain habits of the mound builders which may explain the presence and condition of the lower layer of bones in the Gilder mound. Concerning the water-worn condition of the bones, the writer also hesitates to express an opinion, but in a superficial examination of the collection of bones at Lincoln he failed to see any evidence that they are water-worn. They seem to have merely the appearance of bones which have been buried a long time.

The Gilder mound is of interest anthropologically because it shows that more than one burial took place here, and in this respect it ranks with the Okoboji mound.[17] But it seems to present no evidence whatever of great geological age.

OTHER MOUNDS

Mounds are not uncommon in the vicinity of Florence and Omaha; indeed, they are frequent on the bluffs of the Missouri from Sioux City to Hamburg, Iowa. The writer has found a large number of these mounds, and has examined a few more carefully, and invariably he has found pebbles, flint chips, and shells or fragments of shells of freshwater mussels mingled with a more or less brown-stained soil material, even where human bones were not present, and he has yet to learn of a case in which river mussels were found in what was reported to be loess, in which the materials did not show such relation to mounds. Plate 16, figure 1, shows the location of such a mound near Hamburg, Iowa.

It is clear that the so-called mound builders inhabited the Missouri valley, for they have left numbers of these mounds to bear silent testimony of the presence of their builders, and there seems to be absolutely nothing in the Gilder mound to determine or suggest for it an age greater than that of other mounds in the territory.

Other Geological Considerations

Certain other geological considerations of a more general character which have been presented in connection with this case deserve attention. Professor Barbour has given a section from the Missouri valley to Gilder mound, in which he represents the glacial clay as 15 or 20 feet deep, and

[17] A. S. Logan also reports a mound near Jefferson City, Missouri, with two layers of human bones. See the Kansas City Scientist, vol. v, 1891, p. 164.

FIGURE 1.—LOESS RIDGE AT HAMBURG, IOWA

Capped by mound containing pebbles and mussel shells

FIGURE 2. BLUFF NEAR PRIES LAKE

The uppermost, nearly vertical part only is loess, resting on Kansan drift

LOESS RIDGE AT HAMBURG, IOWA, AND BLUFF ABOVE FLORENCE, NEBRASKA

FIGURE 1.—BLUFF BELOW PRIES LAKE

Shows Kansan drift and loess separated by a foot of Kansan "gumbo," forming an oblique band

FIGURE 2.—THE UNION PACIFIC "CUT-OFF" AT SOUTH OMAHA

This line (X) separates the drift clay below from the two loesses above

SECTIONS AT PRIES LAKE AND SOUTH OMAHA

on this a layer of loess 150 feet thick. He obtained his section practically by following the bluff and road cuts from the vicinity of Pries lake to Gilder mound, and he assumes that because the road cut, nowhere more than 10 feet deep, shows continuous loess from the base of Long hill to the mound 150 feet higher, therefore the loess is 150 feet thick. However, the loess in this region everywhere tends to form a mere mantle extending over the ridges whose cores consist of rock or drift, or both, and the probability is that on Long hill the loess does not exceed 35 feet in thickness. (See also plate 16, figure 2, and plate 17, figure 1.) An exposure three-quarters of a mile north of Pries lake shows a core of drift and glacial joint clay to a height of 95 feet above the road, and this is capped with about 25 feet of fossiliferous loess. (See also plate 16, figure 2.) Numerous exposures on both sides of the Missouri from Sioux City to Kansas City show that the reported thickness of the loess in this region, especially on the west side of the river, has been greatly exaggerated. The great cuts along the new Union Pacific "cut-off" in south Omaha illustrate this fact. The first cut, near the intersection of Thirty-second and B streets, is about 56 feet deep and shows a regular mantle of loess 36 feet deep. The greater cut, between Forty-second and Fifty-third streets, which is about a mile in length and about 100 feet deep (see plate 17, figure 2), shows a similar mantle, consisting of two loesses, the upper yellow loess, about 25 feet deep, and the lower, less uniform, about 8 feet deep. The total thickness of the loess mantle is therefore about 33 feet. Professor Barbour has undoubtedly greatly exaggerated the thickness of the loess on Long hill.

The reference of the loess to glacial times is also extremely unfortunate, for the organic remains in the loess preclude the possibility of a glacial climate during its deposition. Before Professor Barbour can sustain such an assumption he must explain the presence of the fossils in the loess and the possibility under glacial conditions of the existence of the plants necessary to their maintenance; he must explain also the presence of loess and its fossils in the southern states, never reached by glaciers, and in the extra-glacial western territory along the Platte and Republican rivers in Nebraska. However, the discussion of these questions would involve the consideration of the relative merits of the aqueous hypothesis, to some form of which Professor Barbour evidently adheres, and the æolian hypothesis which has distinctly passed its merely conjectural stage.

Summary

The foregoing facts lead to the following conclusions:

1. Gilder mound is an ordinary mound, of interest because it contains two layers of human remains, but it is not unlike other known mounds.

2. The human bones, pebbles, and shells all found their way into the mound by intrusion. The lime nodules were probably formed after the mound had been constructed.

3. The human remains in question were not in undisturbed loess and hence are not loess fossils.

4. These remains present no evidence of the existence of man in the Glacial period, for not only are they not in undisturbed loess, but loess itself is not glacial.

5. Incidentally, a large part of the surface deposit found along the Missouri river, especially on the west side, is glacial clay, and should not be classed with loess, which here seldom exceeds 35 feet in thickness.

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PALEOZOIC AND ASSOCIATED ROCKS OF THE UPPER YUKON, ALASKA[1]

BY ALFRED H. BROOKS AND E. M. KINDLE

(Presented by title before the Society December 31, 1907)

CONTENTS

GEOGRAPHY

The province here to be considered embraces that part of the Alaska-Yukon basin lying adjacent to the International boundary (141st meridian) and stretching westward to the 152d meridian. The Tanana river can be regarded as its southern boundary, and it extends northward to about the 67th parallel of latitude. Most of the observations on which the present paper is based were made in the eastern half of this area.

This region is drained by the Yukon river and its tributaries, the largest being the Porcupine river, joining the Yukon from the northeast at its great bend near the Arctic circle, and the Tanana, flowing westerly, which joins the Yukon about 200 miles to the southwest of the mouth of the Porcupine (see map, figure 1). The region forms a part of the so-

[1] Published by permission of the Director of the U. S. Geological Survey.
Manuscript received by the Secretary of the Society April 7, 1908.

called Plateau region of central Alaska, being the intermontane belt bounded on the south by the ranges of the Pacific mountain system and on the north and east by the Rocky Mountain system.

The topography is characterized by broad, flat-topped, interstream areas, separated by the valleys of a well developed drainage system. The valleys are usually broad and flat, with gentle slopes. Certain exceptions to this characteristic valley type will be noticed below, but of especial importance are the ramparts of the Yukon, lying below the great Yukon flat, and the ramparts of the Porcupine. These topographic forms are probably in part due to recent[a] local warpings, in part to the influence on erosion by character of bedrock.

The dominating feature of the topography is the baselevel character of the upland summits, which represent an uplifted and dissected peneplain. This old land surface is deeply mantled by the products of weathering, while the valley slopes are often buried under a heavy talus. Therefore outcrops of bedrock are not common. The difficulties of deciphering the rather intricate geology of this field lies not so much in its inaccessibility, as is generally supposed, as in the absence of exposures of bedrock. In an overland journey the geologist will often travel for days without seeing a single outcrop, and must perforce map the boundaries of the stratigraphic units solely on the facts gleaned from the weathered surface materials. The general absence of excavations and the heavy coating of moss which nearly everywhere mantles the soil increase the difficulties of geologic mapping. Fortunately the exposures of bedrock are not uncommon along the large watercourses, and this fact alone would justify the publication of this paper, which is based largely on the observations made along the valleys of the Yukon and the Porcupine rivers, supplemented by the results of overland journeys in part made in previous years.

Geologic Investigations

During the past three decades many workers have taken part in the investigation of this general field, and the conceptions of the stratigraphic succession have gradually crystallized into definite form. The character of these studies has varied from the exploratory journeys of Kennicott, Dall, Ogilvie, and McConnell to such detailed examinations of special areas as have been made by Collier and McConnell. These various investigations will be referred to below, and to all of them the writers are indebted for clues to the geology of the region.

[a] Alfred H. Brooks: The Geography and Geology of Alaska. Professional paper no. 45, U. S. Geological Survey, 1906, pp. 278-282.

Robert Kennicott and William H. Dall were the pioneer scientists in this field. In 1861 Kennicott, following the old Hudson Bay route from the Mackenzie river, crossed the divide at the head of the Porcupine and wintered at Fort Yukon,[3] at its mouth. Six years later Doctor Dall, as a member of the Western Union Telegraph expedition, reached the same point by an up-river journey from the mouth of the Yukon.[4]

In 1888 McConnell,[5] of the Geological Survey of Canada, made an exploratory trip from the Mackenzie across to the Porcupine and down that river to the Yukon, then up the Yukon to its junction with the Pelly and Lewes. He was the first to obtain a clue to the bedrock geology of the particular field here to be discussed. The same year Ogilvie,[6] Dominion land surveyor, explored the headwaters of the Porcupine and collected some geologic data.

Two years later Russell[7] carried a geologic reconnaissance from the mouth of the Yukon to its headwaters, returning to the coast by way of the Chilkoot pass. Russell's hasty trip yielded some few notes on the bedrock, but his observations were largely devoted to the problems connected with the surface features.

In 1896 Spurr[8] made the first systematic surveys of any portion of the Alaska-Yukon. His report still remains the standard work of reference on this field, and much of the stratigraphic nomenclature which he introduced has found a permanent place in the literature.

Brooks[9] traversed the eastern end of this field in 1898, and in the following year[10] extended his observations in the same general area. The region lying north of the Yukon was first explored by Schrader[11] in 1899, who two years later extended his[12] investigations northward to the Arctic

[3] William H. Dall: Alaska and its resources. Boston, 1870, p. 349.

[4] Ibid., pp. 74-115.

[5] R. G. McConnell: Report on an exploration in the Yukon and Mackenzie basins, Northwest Territory. Annual Report of the Geological and Natural History Survey of Canada, new series, vol. 74, 1890, pp. 5-144D.

[6] William Ogilvie: Exploratory survey of part of the Lewes, Tatonduc, Porcupine, Trout, Peel, and Mackenzie rivers. Interior Department of Ottawa, 1890.

[7] I. C. Russell: Notes on surface geology of Alaska. Bulletin of the Geological Society of America, vol. 1, 1890, pp. 72-99 and 154-155.

[8] J. E. Spurr: Geology of the Yukon gold district, Alaska. Eighteenth Annual Report, U. S. Geological Survey, part 3, pp. 87-392.

[9] Alfred H. Brooks: A reconnaissance on the White and Tanana basins. Twentieth Annual Report, U. S. Geological Survey, 1900, pp. 425-494.

[10] Alfred H. Brooks: A reconnaissance from Pyramid harbor to Eagle City. Twenty-first Annual Report, U. S. Geological Survey, part ii, pp. 331-391.

[11] F. C. Schrader: Preliminary report on a reconnaissance along Chandlar and Koyukuk rivers, Alaska, in 1899. Twenty-first Annual Report, U. S. Geological Survey, part ii, 1900, pp. 441-486.

[12] F. C. Schrader: A reconnaissance in northern Alaska. Professional paper no. 20, U. S. Geological Survey, 1904.

coast, while Mendenhall[13] at the same time carried an exploration from the mouth of Dall river, tributary to the Yukon, to the Koyukuk and thence to Kotzebue sound. In 1902 Brooks,[14] in company with L. M. Prindle, traversed the western part of this province, in course of an exploration extending from Cook inlet to Rampart, on the Yukon.

These various explorations defined the larger geographic and geologic features of the province and paved the way for the somewhat more detailed investigations to follow. In 1899 McConnell began his detailed studies of the Klondike placer fields, which lie adjacent to the area here discussed, and continued them with some interruption until 1906.[15] The easterly extension of the same general belt of rocks has been the subject of investigations by Keele[16] and Camsell.[17]

The detailed stratigraphic studies on the Alaska-Yukon were inaugurated by Collier[18] in 1902, who gave, however, more particular attention to the coal-bearing terrains which belong to the Mesozoic and Tertiary. These studies were supplemented the following year by Arthur Hollick, who made large collections of fossil plants from the coal-bearing beds exposed along the Yukon. In 1903 Prindle[19] began a systematic study of the geology and mineral resources of the Yukon-Tanana region, which has been continued to the present time. The gold placers being of the first importance, the rocks with which they are associated, namely, the metamorphic schist, have received the first attention from him, but the Paleozoic and Mesozoic stratigraphy has also been touched upon in his reports. Prindle's work was supplemented in 1905 by a geologic reconnaissance made by Stone[20] from Circle to Fort Hamlin.

[13] W. C. Mendenhall: A reconnaissance from Fort Hamlin to Kotzebue sound, Alaska. Professional paper no. 10, U. S. Geological Survey, 1902.

[14] Alfred H. Brooks and L. M. Prindle: An exploration in the Mount McKinley region, Alaska. Bulletin of the U. S. Geological Survey. (In preparation.)

[15] R. G. McConnell: Preliminary report on the Klondike gold fields, Yukon district, Canada. Geological Survey of Canada, no. 687. Ottawa, 1900.

Report on the Klondike gold fields, part B, vol. xiv, Geological Survey of Canada, no. 884. Ottawa, 1905.

Report on gold values in the Klondike high level gravels. Geological Survey of Canada, no. 979. Ottawa, 1907.

[16] J. Keele: Report on the Upper Stewart River region, Yukon. Geological Survey of Canada, no. 943. Ottawa, 1906.

[17] C. Camsell: Report on the Peel river and its tributaries. Geological Survey of Canada, no. 951. Ottawa, 1906.

[18] Arthur J. Collier: Coal resources of the Yukon basin. Bulletin no. 218, U. S. Geological Survey, 1903.

[19] L. M. Prindle: The gold placers of the Fortymile, Birch Creek, and Fairbanks districts, Alaska. Bulletin no. 251, U. S. Geological Survey, 1904.

L. M. Prindle and F. L. Hess: The Rampart gold placer region, Alaska. Bulletin no. 280, U. S. Geological Survey, 1906.

L. M. Prindle: The Yukon-Tanana region. Description of the Circle quadrangle. Bulletin no. 295, U. S. Geological Survey, 1906.

[20] R. W. Stone: A geologic reconnaissance from Circle to Fort Hamlin. Bulletin no. 284, U. S. Geological Survey, pp. 128-131.

To complete this sketch of the history of geologic studies in this province, it will be necessary to enumerate the paleontologic collections made by previous investigators. The first reference to fossils from the Upper Yukon basin appeared in a paper by Meek,[21] published in 1867. In this five Devonian species, reported to have been found on the Porcupine river in Russian America, are included with the fossils described from the Mackenzie river. These fossils, which are stated to have been obtained in part by Kennicott from a missionary in course of the journey already referred to, are credited to three different localities on the Porcupine. The locality described for *Favosites polymorpha* would be not far from Fort Yukon, in the Yukon flats, or nearly 100 miles from the nearest outcrop of bedrock. Examination of the specimens shows that they came from a rock material different from any of the fossiliferous horizons of the Devonian observed by the writers either on the Porcupine or Yukon rivers. It appears probable that the five species credited to the Porcupine river were all obtained from the Reverend W. W. Kirby, and that they all came originally from the Mackenzie and not from the Yukon.

In his account of the journey up the Yukon in 1867, Dall mentions having found, "just above the Ramparts, pebbles of Niagara limestone with its characteristic fossils."[22] No information concerning the species represented in these pebbles appears in connection with this observation nor in subsequent papers.

McConnell reports having found *Atrypa reticularis* and crinoid stems in the yellow limestones of the lower Ramparts while descending the Porcupine river in 1889, and states that these limestones "are probably referable in part at least to the Devonian."[23] The writers' observations seem to indicate that only Silurian and Ordovician rocks are present in the lower Ramparts. *A. reticularis* is a common species in the Silurian fauna of the lower Ramparts, and the specimens obtained by McConnell probably represent that fauna.

In 1896 Spurr made a collection of fossils from the white limestone near Nation river, on the Yukon, which demonstrated the presence of a Carboniferous horizon in the region.[24] He also obtained some obscure

[21] F. B. Meek: Remarks on the geology of the Mackenzie river, with figures and descriptions of fossils from the region in the museum of the Smithsonian Institution, chiefly collected by the late Robert Kennicott, Esq. Transactions of the Chicago Academy of Science, vol. 1, 1867, pp. 61-114, pls. 11-15.

[22] W. H. Dall: Exploration in Russian America. American Journal of Science, second series, vol. 46, 1868, p. 98.

[23] R. G. McConnell: Report on an exploration of the Yukon and Mackenzie basins. Annual Report of the Geological and Natural History Survey of Canada, new series, vol. 4, 1890, p. 133D.

[24] J. E. Spurr: Geology of the Yukon gold district. Eighteenth Annual Report, U. S. Geological Survey, part 3, 1898, p. 170.

Provisional stratigraphic Table

System.	Series.	Lithologic character.	Locality.
	Recent.......	Silts, sands, and gravels...	Throughout the province.
Quaternary....	....	(Unconformity.)	
	Pleistocene...	Chiefly silts, with some gravels. (Invertebrate fossils, fossil plants.) (Unconformity.)	Throughout the province.
Tertiary.......	Eocene (Kenai).	Friable conglomerates and sandstones and shales with lignitic coals. (Fossil plants.) (Unconformity.)	Along Yukon and in adjacent area.
Cretaceous.....	Upper Cretaceous.	Conglomerates, sandstone, slate, and shale, cut by granite. (Invertebrate fossils.) (Unconformity.)	Wolverine mountains, Quail creek, near Rampart.
	Lower Cretaceous or Upper Jurassic.	Siliceous slate and quartzites, with some tuff and a little limestone, cut by basic dikes. (Invertebrate fossils.) (Unconformity.)	Upper Yukon river, between Fourth of July and Coal creek.
	Triassic......	Limestones and slates. (Invertebrate fossils.) (Conformity?)	Yukon river, near mouth of Nation river, Upper White River valley, Stewart River basin.
Carboniferous..	Upper Carboniferous.	Heavy limestones. (Invertebrate fossils.) (Unconformity?)	Yukon river, near mouth of Nation river, Upper White River valley.
		Nation river formation. Conglomerates, sandstones, and shales. (Plant fragments.) (Unconformity.)	Yukon river, at mouth of Nation river.
Carboniferous..	Lower Carboniferous.	Calico Bluff formation. Thin-bedded limestone, slates, and shales. Some igneous rocks. (Invertebrate fossils.) (Conformity.)	Calico bluff and other points on Upper Yukon river; also on Porcupine river.
	Upper Devonian.	Black and gray shales and slates. (A few invertebrate fossils.)	Calico bluff, on Yukon and on Porcupine.

Provisional stratigraphic Table—Continued

System.	Series.	Lithologic character.	Locality.
Devonian......	Middle Devonian.	Siliceous white crystalline limestone (invertebrate fossils), associated with a large amount of igneous material. Blue limestone (Salmontrout limestone), overlaid by shales. (Invertebrate fossils.) (Unconformity?)	Occurs along Yukon river and at old Rampart village on Porcupine river and probably in other parts of the basin of Porcupine river.
Devonian?....	....	Heavy blue and white siliceous limestone (fragmentary invertebrate fossils), with slates, quartzites, and thin-bedded limestones. (Stratigraphic position doubtful.)	Yukon river, 8 miles below Woodchopper creek.
Silurian?......	....	Fine conglomerates, cherts, graywackes, and slates, with some limestones. (No fossils; age determination doubtful.)	In region lying between Fairbanks and Rampart.
Silurian........	Middle.......	Magnesian limestone. (Invertebrate fossils.) (Conformity?)	Porcupine river. The same formation probably occurs in the Yukon-Tanana region.
Ordovician	....	Non-magnesian limestones. (Invertebrate fossils.) (Unconformity?)	Porcupine river. Probably present in other parts of the Yukon basin, but not positively identified.
Pre-Ordovician.	....	Slates and quartzites, with some limestones. (No fossils.)	Porcupine river.
Pre-Ordovician?	....	Quartzites, quartz, schists, mica-schists, and limestones. Includes some gneisses, granite, and greenstone intrusives. Probably equivalent to the slates and quartzites (pre-Ordovician) of the Porcupine river. Includes the Birch Creek schists and Nabesna series.	Extremely developed in the Upper Yukon basin.

Such a generalization of the stratigraphic sequence in a region as little known as Alaska of necessity implies correlations which are by no means definitely established. For example, all the elevated silt and gravel deposits are here placed in the Pleistocene, while it is by no means impossible that some of them may not be older. Again, the lignite-bearing beds are all included in the Eocene, yet some of these may be older. In considering the pre-Carboniferous horizons, many of which are both unfossiliferous and intricately folded, the problem becomes still more difficult; therefore the lower part of the stratigraphic column, as here presented, must be considered only as suggestive, except for specific sections where the age is definitely established as shown in succeeding pages.

Attention has already been directed to the general strike lines, which, paralleling the dominant topographic features of Alaska, trend northwesterly to about the 146th meridian, then bend southwesterly. While locally there are many variations from these trends, nevertheless the northwest-southeast and northeast-southwest structural lines dominate. It will be shown that these two structures have dominated all the crustal movements since pre-Ordovician times.

The general sequence presented in the above table involves, as has been stated, certain correlations based on very imperfect data. The evidence relating to this matter will be presented in some detail, taking up each period separately. The Mesozoic and later terrains will, however, only be briefly considered in this paper.

PRE-ORDOVICIAN

The terrains here assigned to the pre-Ordovician embrace two very different groups of rocks, believed to be of synchronous age. In the one are included the quartzites and associated sediments of the Porcupine basin, and in the other the mica quartzites, mica schists, and crystalline limestones, which are widely distributed in the Yukon basin.

A series of thin-bedded quartzites with intercalated beds of shale and some limestones, which outcrop on the Porcupine river near the International boundary, are described in the accompanying paper by Mr Kindle. These rocks are indurated, but not metamorphosed, and, so far as known, are not cut by any igneous rocks, with the exception of a very few small dikes. Mr Kindle assigns this series to the pre-Ordovician on stratigraphic grounds.

The metamorphic rocks, assigned to pre-Ordovician age, occur in two areas within this province. The smaller (see map, figure 1) forms a part of a belt stretching across northern Alaska and is divided by Schra-

FIGURE 1.—*Geologic Sketch Map of Upper Yukon Basin*

der[29] into several formations. These include mica, quartz mica, and amphibole schists, with some massive granite. Schrader provisionally assigned these rocks to the Silurian, but, as has been shown elsewhere,[30] the evidence is equally strong for a pre-Silurian age. These schists strike northeast into the unexplored region lying between Porcupine river and the Arctic ocean, and are believed to represent metamorphic phases of the pre-Ordovician quartzites and slates of Porcupine river already referred to. This correlation does not now admit of proof.

The southern and larger area of the schistose rocks crosses the Yukon above the International boundary, then extends northwest parallel to the main valley (see maps, figures 1 and 2) to about the 146th meridian, where it bends to the southwest and finally passes underneath the alluvium of the Tanana valley. On the north the boundary of these schists is well defined, being marked by a belt of Paleozoic and younger rocks. Less is known of the southern boundary, but it is in part defined by areas of younger Paleozoic, Mesozoic, and Tertiary sediments.

These metamorphic rocks are dominatingly made up of quartz and mica schists, quartzites, and crystalline limestones. These limestones in some places, as in the Fortymile and White River regions, occupy considerable areas and in part form an integral member of the schists, but may be in part younger terrains which have been infolded with them. In the latter case they may be found to be equivalent in age to some of the Paleozoic limestones to be described below. Intrusions are not uncommon in this metamorphic series and are for the most part acid rock. Of these, granites are the most abundant and occur both in massive and gneissoid phases, and in parts of the province occupy considerable belts. These granites, gneissoid granites, and gneisses were long believed[31] to belong to the Archean, but recent studies, notably those of McConnell and Prindle, have shown that most of these are altered intrusives.

This southern belt of metamorphic rocks was first described by Spurr,[32] who termed the quartzites and mica schist the Birch Creek series, and the calcareous phases the Fortymile series. The earlier work of Dawson[33]

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[29] F. C. Schrader: Preliminary report on a reconnaissance along the Chandlar and Koyukuk rivers. Twenty-first Annual Report, U. S. Geological Survey, part 2, pp. 471-475.

F. C. Schrader: Reconnaissance in northern Alaska. Professional paper no. 20, U. S. Geological Survey, pp. 56-58.

[30] Alfred H. Brooks: The geography and geology of Alaska. Professional paper no. 45, U. S. Geological Survey, pp. 211-218.

[31] See "The Geography and Geology of Alaska." Professional paper no. 45, U. S. Geological Survey, pp. 210-212.

[32] The geology of the Yukon gold district. Eighteenth Annual Report, U. S. Geological Survey, part III, pp. 140-156.

[33] G. M. Dawson: Report on an exploration of the Yukon district. Geological Survey of Canada, no. 629. Ottawa, 1898.

and McConnell[34] had indicated that a zone of similar metamorphic rocks stretched southward into British Columbia. The later investigations of McConnell and his associates have yielded much additional information in regard to these terrains.

In the Klondike district,[35] McConnell recognizes only one group of altered sediments—the Nasina series. This name had previously been applied by Brooks[36] to a group of schists and crystalline limestones exposed along the lower White river, and he suggested their probable equivalency to Spurr's Fortymile and Birch Creek series. McConnell traced these metamorphics westward from this type locality into the Fortymile River basin and proved that they were an extension of the rocks described by Spurr. He too was unable to differentiate them into two formations. The conclusion that the crystalline limestones and schists can not be differentiated into two formations, at least on the basis of reconnaissance work, finds support by the recent studies of Prindle[37] in the Fortymile region.

Keele, of the Canadian Survey, has found what appears to be a southeasterly extension of the Klondike metamorphic rocks in Stewart River region. These he describes[38] as made up of quartzites, mica schists, and crystalline limestones and provisionally correlates them with the Nasina series.

The intrusives of this belt of metamorphic rocks vary greatly in composition and texture, but are chiefly acidic and intermediate granular rocks. All the earlier workers in this field assigned to the Basal Complex[39] a series of gneissoid rocks which were believed to have been folded and metamorphosed previous to the deposition of the Birch creek or Nasina series. In such parts of the region as have been studied in greater detail this conclusion has been found to be erroneous, and it seems improbable that any rocks older than the Nasina have been found. Many of the gneisses are found to be either sheared granites or quartz porphyries, which were intruded in the metamorphic sediments and subsequently infolded with them. These rocks, which occupy considerable areas, have been termed the "Pelly gneiss" by McConnell, who has pointed

[34] Opus cited. See also "Geological Map of the Dominion of Canada." Western sheet, no. 783.

[35] Report on the Klondike gold field. Geological Survey of Canada, Annual Report, part B, vol. xiv, pp. 10B-23B.

[36] A reconnaissance in the White and Tanana River valleys. Twentieth Annual Report, U. S. Geological Survey, part vii, pp. 465-467.

[37] Unpublished notes.

[38] J. Keele: Report on Upper Stewart River region, Yukon. Geological Survey of Canada, Ottawa, 1906, no. 943, p. 14c.

[39] Geography and geology of Alaska. Professional paper no. 45, U. S. Geological Survey, pp. 208-210.

out their probable genesis. In addition to these, massive granites are not uncommon. There are also some rocks having a primary gneissic structure whose genesis is uncertain. Many greenstones and greenstone schists are associated with the metamorphic sediments, and are probably for the most part derived from intrusives.

There is little clew to the age of the granitic rocks. Prindle has described a granite stock cutting Cretaceous sediments in the Rampart region. This probably represents a later phase of injection than that represented by the gneisses. In the foothills of the Alaska range south of the Tanana there are extensive exposures of a gneissoid rock which were first regarded as basal, but which has been proved by Prindle[40] to be an altered rhyolite associated with cherts and slates, probably of Silurian or Devonian age. These facts suggest that the other gneisses of similar character may be of post-Ordovician age.

The character of the metamorphic and crystalline rocks of the eastern part of the area is well illustrated in the highlands traversed by the lower White river. Here a belt of gneissoid and granitic rocks is flanked on the north and south by metamorphic sediments—a relation which was interpreted as indicating that the former were a part of the Basal Complex, but which later investigations have shown to be for the most part altered igneous rocks intrusive in the sediments. It is not to be denied, however, that there are some gneisses whose structure is primary, and it will remain for more detailed investigations to determine what the genesis of these rocks is and their relation to the sediments and known intrusives.

The section extends from the Yukon river to the White-Tanana flat, a distance of about 50 miles. The rocks lying north of the gneisses and forming the type section of the "Nasina series," as originally defined, are dominatingly made up of quartz and mica schists, often finely laminated. One belt of white crystalline limestones, with intercalated phyllites carrying some graphite, is exposed about 10 miles from the mouth of White river, and this appears to be an integral part of the metamorphic series. Greenstone schists, largely made up of secondary minerals, and whose color is due to the presence of actinolite and chlorite, which are probably altered igneous rocks, occur widely distributed, but do not form any considerable part of the mass of the metamorphic rocks.

The southern belt of metamorphic sediments of this section are not as highly crystalline as those above described. They are dominatingly made up of micaceous and graphitic schists and phyllites. These rocks locally become calcareous, grading into impure schistose limestones.

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[40] L. M. Prindle: The Fairbanks and Rampart quadrangles. Bulletin no. 337, U. S. Geological Survey, p. 28.

Gneissic rocks, which form a belt some 20 miles wide, separating these two areas of metamorphic sediments, are composed chiefly of granitic rocks. Biotite and hornblende are the prevalent dark silicates of these gneissoid rocks, and most of them show evidence of shearing. Porphyritic phases dominate, and in many places these have been altered to augen gneisses. Mica schists are not uncommon within the gneissic belt, and these may be included masses of sedimentary rocks. As in the sedimentary rocks, greenstone schists are not uncommon, intercalated with the gneisses, and also occur in a belt several miles in width along the southern margin of the crystalline area. The gneisses are for the most part undoubtedly igneous intrusives which have been deformed subsequent to their crystallization. In addition to these, massive intrusives, probably representing a later injection, are not uncommon. These are lithologically similar to the gneissoid granites. Some aplite dikes, apparently the most recent injections, deserve mention.

This entire zone of metamorphic rocks strikes in a northwesterly-southeasterly direction. The dip of the foliation and of the bedding in the few places where it could be determined is prevailingly to the north. There are two general systems of jointing which roughly parallel these two directions. To such an extent have the rocks been deformed that it is impossible to determine the structure, though it has been suggested that the gneisses represent the eroded core of an anticlinal axis. At a locality on the lower White river a concentric arrangement of the strata was noted encircling in part, at least, one of the massive granite stocks and at variance with the general structural lines. This suggests that this granite was intruded after the crustal movements which determined the general structures.

There is practically no clew to the thickness of the sediments here described, but it probably includes many thousand feet of strata. The limestone member, so far as determined, is at least 1,000 feet thick.

Summing up the evidence from this section, it would appear that a great thickness of strata had here been deposited which was deeply buried, metamorphosed, and intruded by both basic and acid igneous rocks. The whole series was then intensely deformed by crustal movements, and later a second intrusion of granitic rocks took place.

The geological section exposed between the Yukon river at Circle and Fairbanks, on the Tanana, includes what is probably a typical example of the metamorphic rocks of the western end of the field. Here the entire series is made of sediments, with the exception of a few stocks of intrusive granites. Two rocks are typical of the entire belt—a schistose quartzite and a mica schist, often graphitic. The quartzite is more typi-

cal of the northern end of the section, and the mica schist of the southern end. Some greenstones are present, but are relatively scarce. Mr Prindle has found some crystalline limestones associated with the schists in this general region, but these were not studied by the writers. The granitic rocks occurring in stocks and dikes, which are not uncommon, are usually massive, but are sometimes sheared along their peripheries.

The general strike is northeasterly, with prevailingly northerly dips, and usually at a steep angle. Evidence of close folding is usually found where the bedrock is well exposed. The thickness of this arenaceous series, to be measured in thousands of feet, can probably never be determined, even with the most minute stratigraphic work.

The data at hand justify the statement that, below the rocks of known age (certainly older than the Devonian and probably than the Ordovician), there is a complex of metamorphic sediments and igneous rocks which is widely distributed in the upper Yukon basin. As some of these are probably of synchronous age with the quartzite and slates of the Porcupine river, which are below the Ordovician, we are probably justified in classing them all as pre-Ordovician, with the reservation that there may be some younger metamorphosed Paleozoic terrains infolded with them. The evidence now at hand indicates that the rocks formerly classed as "Archean basal granites" or "Basal Gneiss" are for the most part altered igneous rocks which have been injected since the deposition of the sediments.

If one were to venture on more definite correlations, it would be to regard the Birch Creek and Fortymile series, as defined by Spurr, to be the equivalent of the Nasina series as used by McConnell and Brooks. The term "Birch Creek schists," as used by Prindle in his more recent publications, would represent either the lower or less calcareous phase of the Nasina series or might indicate a decrease in the percentage of calcareous matter to the westward. The latter theory appears to be borne out by the fact that the metamorphic rocks, described by Schrader north of the Yukon under the names Rapid schists,[41] Lake quartzite schist, and Totsen[42] series, which are here correlated with Prindle's Birch Creek schist, are essentially non-calcareous rocks. A general correlation of these metamorphic rocks with the Kigluaik group of the Seward peninsula[43] is probably justified. The Kigluaik embraces a great thickness of gneisses,

[41] F. C. Schrader: Preliminary report on a reconnaissance in the Chandlar and Koyukuk rivers, Alaska. Twenty-first Annual Report, U. S. Geological Survey, part ii, pp. 473-474.

[42] F. C. Schrader: Reconnaissance in northern Alaska. Professional paper no. 20, U. S. Geological Survey, pp. 58-60.

[43] Arthur J. Collier, Frank L. Hess, and Alfred H. Brooks: The gold placers of a part of the Seward peninsula. Bulletin no. 328, U. S. Geological Survey. (In print.)

LOWER END OF CALICO BLUFF, YUKON RIVER

Showing relation of Devonian shales and Calico Bluff limestones and shales (Carboniferous). Photograph by C. L. Andrews

schists, and crystalline limestones, with many intrusives, and is known to be older than the Ordovician. The altered igneous rocks occurring in the metamorphic complex of Yukon can be conveniently grouped together under the name "Pelly gneisses." They appear to be in part derived from granitic, in part from rhyolitic rocks. There is some evidence of their having been, in part at least, intruded as late as the Silurian. Massive granites, in part as late as the Cretaceous, occur widely distributed as stocks and dikes.

ORDOVICIAN

The only Ordovician fossils which have been found in this province are those described by Mr Kindle (see pages 323-324) as occurring in a blue-gray limestone which outcrops on the Porcupine river near the International boundary and has a thickness of about 600 feet (see page 323). It is possible that some of the crystalline limestones now regarded as forming an integral part of the pre-Ordovician schists may represent infolded rocks of a later age, and the Ordovician may be represented by some of these. Of the adjacent provinces the Ordovician is known to be extensively developed in the Seward peninsula[44] alone, where it is represented by at least a part of the Port Clarence[45] limestone, with a thickness of probably several thousand feet. Some carbonaceous shales and limestones occur in the upper Kuskokwim valley which carry graptolites, referred by Charles Schuchert to the Ordovician.[46]

Dawson[47] has described a black shale formation having a thickness of some 1,500 feet, which is exposed on the lower Dease river near latitude 60° and which carries graptolites assigned by Lapham to the middle Ordovician.

These occurrences of deep-water sediments at such widely separated localities as Dease river, Porcupine, Kuskokwim, and Seward peninsula indicate the vast extent of the Ordovician sea in which they were laid down. The relation of the Ordovician to the older terrains has not been established, but is probably one of unconformity. There is some evidence to indicate a profound metamorphism of the rocks here classed as pre-Ordovician previous to the deposition of any of the known Paleozoic terrains. On the other hand, however, in the Porcupine valley the only

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[44] Arthur J. Collier, Frank L. Hess, P. S. Smith, and Alfred H. Brooks: The gold placers of a part of the Seward peninsula. Bulletin no. 328, U. S. Geological Survey.

[45] The Port Clarence may be in part Silurian.

[46] Alfred H. Brooks and L. M. Prindle: An exploration in the Mount McKinley region. Bulletin no. —, U. S. Geological Survey. (In preparation.)

[47] George M. Dawson: Report on Yukon district and adjacent portions of British Columbia. Geological Survey of Canada, Annual Report, 1887, part B, pp. 94B-95B.

locality where the Ordovician has been found in contact with older rocks, the latter had been little altered. There is, therefore, little clew to the age of this first great period of diastrophism.

SILURIAN

Terrains which will probably be ultimately referred to the Silurian find a wide distribution in central Alaska, but only a few of them have yet yielded definite Silurian fossils. In the second part of this paper Mr Kindle describes the Silurian of the Porcupine, embracing two different terrains—a lower, made up of about 2,500 feet of magnesian limestone and black shale, and a higher, including about 25 feet of black shale, lying immediately below and unconformable with Devonian sediments.

A westerly extension of these Porcupine rocks would carry them into the Koyukuk basin (see map, figure 1), where Schrader has given the name Skajit formation to some crystalline limestones and schists which he provisionally assigned to the Silurian[48] on the evidence furnished by an obscure fossil. It seems quite likely, however, that the Skajit may belong with the metamorphic schist series.

The section studied by the writers along the upper Yukon does not include any rocks which have been definitely assigned to the Silurian. There is, however, a group of heavy crystalline limestones, slates, and quartzites of unknown age which may prove to be Silurian, but are here included with the description of the Devonian.

In the southwestern part of the province, especially in the region lying between Fairbanks and Rampart, there is an extensive development of rocks embracing cherts, slates, and feldspathic sandstones and quartzites, with considerable greenstone and some limestone, which have been provisionally assigned to the Silurian.[49] These are younger than and unconformable with the metamorphics and appear to be older than the Devonian terrains of the same region. As, however, they are lithologically very similar to the Devonian and have yielded (Silurian) fossils at only one locality, it is quite possible that a part of this series may be of Devonian age. The Silurian fossils were found by Prindle in a heavy gray limestone on Quail creek about 12 miles northeast of Rampart. Mr Kindle[50] reported on these fossils as follows:

[48] F. C. Schrader: Reconnaissance in northern Alaska. Professional paper no. 20, U. S. Geological Survey, pp. 56-58.

[49] L. M. Prindle: The Fairbanks and Rampart quadrangles. Bulletin no. 337, U. S. Geological Survey, pp. 18-20.

[50] L. M. Prindle: The Fairbanks and Rampart quadrangles. Bulletin no. 337, U. S. Geological Survey, pp. 21-22.

"The chief interest of the collection lies in the lamelli-branch fragments, which represent a very large thick-shelled form, which it appears almost certain is specifically identical with a shell occurring in the Glacier Bay limestones and similar beds at Freshwater bay, in southeastern Alaska. This shell has been referred to the genus *Megalomus* in southeastern Alaska and considered to belong to a late Silurian fauna.

"The apparent identity of the Quail Creek specimens with those at Glacier bay makes it highly probable that the two limestones are of the same age, thus indicating a late Silurian age for the limestones of Quail creek."

Though this determination indicates a Silurian age for the limestone, it is by no means certain that the associated fragmental rocks belong to the same terrain. Therefore, while it is safe to assume that the Silurian is present in this district, some of the rocks which have been assigned to it may be of Devonian age. On the other hand, it will be shown that some of the rocks, including slates, limestones, and quartzites, exposed along the upper Yukon and here assigned to the Devonian, may be of Silurian age.

It seems probable that this aggregate of rocks comprises a thickness of several thousand feet, but, as it is extremely intricately folded, estimates of thickness are little more than guesses. These terrains strike northeasterly toward Beaver creek, where a belt of similar rocks has been found by Prindle[51] and Hess flanked by Devonian beds.

A late Silurian fauna, to which the Quail Creek fauna is closely related, is also known to occur at Glacier[52] and at Freshwater[53] bays, in southeastern Alaska. These are clearly younger than the fauna of the Porcupine district already referred to. The unique character of this fauna does not suggest comparison with any other known Silurian fauna save in a most general way. It is supposed to represent a horizon near that of the Guelph.

The facts presented show an extensive development of Silurian deep sea sediments in the Porcupine district, the possible presence of similar rocks in the Yukon section, and the probability that a group of fragmental rocks extensively developed in the Rampart region belongs to the same system. Regarding the Silurian of other parts of the territory it has only been definitely recognized as a heavy limestone bed in southeastern Alaska, which will be described below. The Port Clarence[54]

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[51] L. M. Prindle and F. L. Hess: The Rampart gold placer region, Alaska. Bulletin no. 280, U. S. Geological Survey, pp. 18-20.

[52] A. H. Brooks: A preliminary report on the Ketchikan mining district, Alaska. Professional paper no. 1, U. S. Geological Survey, 1902, p. 19.

[53] E. M. Kindle: Notes on the Paleozoic faunas and stratigraphy of southeastern Alaska. Journal of Geology, vol. xv, 1907, p. 323.

[54] Arthur J. Collier, Frank L. Hess, P. S. Smith, and Alfred H. Brooks: The gold placers of parts of the Seward peninsula. Bulletin no. 328, U. S. Geological Survey, pp. 73-79.

limestone on the Seward peninsula, a very massive bed, is either Silurian or Ordovician, and in any event the Silurian is probably represented in some of the overlying schistose rocks.

The possible correlations between these Alaskan Silurian terrains, as well as those of adjacent provinces, can best be expressed in terms of paleontology. This will be here attempted, together with some suggestions as to the possible migrations of faunas; but it should be remembered that the data at hand is far from being complete, and the collections have not yet been studied in detail.

The Porcupine River fauna (see list, page 325) contains species which link it with the Silurian faunas of both Europe and America. Of these *Rhynchotreta cuneata*, var. *Spirifer nobilis*, and *Pentamerus oblongus* have long been known in both European and American faunas. The peculiar little twisted brachiopod *Streptis greyi* has been recognized at but one other American locality, however. Williams[55] has reported it from the Saint Clair limestone fauna of Arkansas. In Europe it occurs in the Silurian of Bohemia, in England, and at the island of Gotland.

The Silurian fauna of the type represented by the species of the Porcupine River fauna is known to have a wide distribution throughout the world. It is well known in various parts of Europe and has been recognized in regions as remote as China,[56] New Zealand,[57] and Australia.[58]

Another, but smaller, Middle Silurian fauna has been found in southeastern Alaska, on Kuiu island, nearly 1,000 miles southeast of the Porcupine River locality. This fauna occurs in the midst of a limestone series which appears to be 2,000 feet or more in thickness, much of which seemed to be barren. Upward these limestones appear to terminate with volcanic breccias, while below they pass into cherts and argillites of undetermined age.

The discovery in the Porcupine section of a distinctively Middle Silurian fauna representing the cosmopolitan fauna of Europe and America presents some points of interest in its bearing on the question of the route of intermigration of the European and American Silurian faunas and the location of the hypothetical western shore of the Silurian sea in America. In recent years some geologists have held that the Silurian rocks were not represented in western America. "Like the older formations of the Silurian, the Niagara has not been identified with certainty

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[55] American Journal of Science, vol. 48, 1894, p. 331.

[56] F. von Richthofen: China, vol. 4, pp. 34-74; Memoire de la Société Royale des Sciences de Liege, second series, vol. 6, 1876.

[57] Quarterly Journal of the Geological Society of London, vol. 41, 1885, p. 199.

[58] Memorandum of the Geological Survey of New South Wales, Paleontology, no. 6, 1898.

in the western part of the continent."[59] Reported occurrences of the Silurian west of the Mississippi valley have been questioned,[60] and Weller has stated "that the greater part of this region (west of the Mississippi valley) was above sealevel during Silurian time. This leaves the North as the only available outlet for the interior epicontinental sea."[61] Recently Chamberlin and Salisbury have stated, with a reservation, that "it would appear that a large part of western North America was land during the Silurian period."[62]

The hypothetical western shoreline of the Silurian sea as drawn by Weller runs northward of Arkansas slightly to the west of the Mississippi, in the United States, and well to the eastward of the Mackenzie river, in British Columbia. Weller has given good reasons for disbelieving that the route of intermigration between the interior American and European Silurian provinces was by way of New York and to the eastward, which would be the geographically most direct one. He has presented the available evidence favorable to the view that the route of intercommunication was by way of Hudson bay, Greenland, and Spitzbergen, and, in the absence of evidence of Silurian faunas in the Northwest, concludes that the path of migration was by this northeastern route.[63] The discovery of a Middle Silurian fauna in northern and southeastern Alaska requires the shifting of the provisional boundary of the Silurian sea alluded to above at least 1,000 miles to the westward in the northern third of the continent. It indicates also that the Alaskan route, by way of Siberia, as well as the Hudson Bay and Greenland route, must be considered as a possible and, in the opinion of the writers, a probable route of intermigration between the European and interior American faunas.

The absence in the American pre-Silurian rocks of any fauna from which the Silurian fauna could have been derived compels the conclusion that many of its more distinctive elements entered the American Silurian sea from a foreign center of dispersion.

The collections of various exploring expeditions have shown the presence of a Silurian fauna at a number of points in the Arctic islands which fringe the northeastern part of the continent. For a knowledge of these collections we are indebted largely to Koenig,[64] Salter,[65] Houghton,[66]

[59] T. C. Chamberlin and R. D. Salisbury: Geology, vol. 2. Chicago, 1906, p. 384.
[60] Chicago Academy of Science Bulletin no. iv, 1900, p. 17.
American Geologist, vol. xviii, 1896, pp. 31-33.
[61] Journal of Geology, vol. vi, 1898, p. 696.
[62] Chicago Academy of Science Bulletin no. 4, part 1, 1900, p. 17.
[63] Ibid., pp. 12-22.
[64] Observations on the rock specimens collected during the first polar voyage of Captain Perry. Appendix to Perry's voyage for the discovery of a northwest passage. London, 1824.

Meek,[67] Etheridge,[68] and Emerson.[69] The recent explorations of Low[70] and Schei[71] have added to our knowledge of these northeastern faunas. The several papers by these authors show that a large percentage of the species of this northeastern American Arctic fauna is common to the Middle Silurian of Europe and the interior of America, with which the Alaskan fauna is affiliated.

Whether the Silurian fauna of the Mississippi valley, Canada, and Arctic America received its foreign element via a northeastern or a northwestern route can not perhaps be conclusively determined with our present knowledge, but some of the considerations which seem to point to the latter conclusion may be stated briefly.

To the northeast of the north Greenland Silurian the nearest known Paleozoic rocks are those of Spitzbergen; but these do not include the Silurian, so far as known. Moreover, a marine trough showing depths of from 10,000 to 15,000 feet separates the land masses of Greenland and Spitzbergen. Turning to northwestern America, we find in sharp contrast with this a continuous continental shelf connecting the Alaskan, Asiatic, and European coasts. The theory of the relative fixity of the great marine troughs lends probability to the supposition of littoral conditions having existed during the Silurian in the general region of the Alaskan and Siberian coasts. On the other hand, the comparatively great depth of the sea to the northeast of Greenland makes unlikely the existence of a shoreline across it during the Silurian, which would have been required for trans-Atlantic migration of faunas in that region.

But little is known of the Silurian fauna of Siberia. Silurian rocks are reported to occur, however, in the new Siberian islands and in the Upper Yenisei River valley.[72]

These occurrences of the Silurian in Siberia, in the intermediate region between the Silurian sections of the Urals and Alaska, leads us to expect

[65] Arctic Silurian fossils. Appendix, p. ccvii, to Journal of a voyage in Baffins bay and Barron straits in the years 1850-51, etc., by P. C. Southerland. London, 1852.

[66] Geological account of the Arctic archipelago. Appendix IV to A narrative of the discovery of the fate of Sir John Franklin, etc., by Captain M'Clintock. Berlin, 1860, pp. 341-372, with map.

[67] Preliminary notice of a small collection of fossils found by Doctor Hays on the west shore of Kenneday channel. American Journal of Science, second series, vol. 40, p. 31.

[68] Palæontology of the coasts of the Arctic lands visited by the late British expedition under Captain Sir George Nares. Quarterly Journal of the Geological Society of London, vol. 34, pp. 568-639, pls. 25-29.

[69] On the geology of Frobisher bay and Field bay. Appendix III to Narrative of the second Arctic expedition made by C. F. Hall. Washington, 1879.

[70] New Land. Four years in the Arctic regions, by Captain Otto Sverdrup, with geological appendix to vol. ii by P. Schei, 1904, pp. 456-458.

[71] The cruise of the *Neptune*. Report on the Dominion government expedition to Hudson bay and the Arctic islands, by A. P. Low, Ottawa, 1906, pp. 322-336.

[72] Ed. Suess: La face de la terre, tome iii, 1902, pp. 24-52.

the discovery of other Silurian rocks in Siberia in the future which will more closely connect the Silurian faunas of northeastern Europe and Alaska.

In this connection the known distribution of the peculiar brachiopod *Streptis greyi* deserves consideration. It occurs in England, the island of Gotland, Bohemia, Alaska, and Arkansas, while it is entirely unknown east of the Mississippi river and in northeastern America. This peculiarly developed species forms an important connecting link between the faunas of Arkansas, Alaska, and Europe, and its apparent absence from the eastern third of America points toward a northwestern rather than a northern or northeastern connection between the Silurian faunas of Europe and America.

DEVONIAN

Devonian terrains are known to be widely distributed in the Upper Yukon basin, but their succession is but imperfectly determined. As rocks of this period are well developed along the Yukon between Eagle and Circle, and as their stratigraphic relations have been more closely studied in this field than in any other part of the province, it will be well to describe it in some detail. Some of the terrains here assigned to the Devonian are included in Spurr's[73] "Rampart series." This fact has led to a rather loose use of the term "Rampart series," and it has been made to include all the Devonian of the Yukon region, especially where it contains any greenstones.

The Devonian probably includes a number of well defined stratigraphic units which will be referred to; these could not be differentiated on the accompanying map because of lack of detailed information (see map, page 278). First the geographical distribution of the Devonian in this area will be considered (see map, figure 2), and then the stratigraphic succession so far as it has been determined. Between Eagle and Calico bluff there is a series of rocks, including drab shales, with some feldspathic sandstones and black slates and shale, which are assigned to the Devonian. A second belt of rocks, which are probably Devonian, including quartzites and limestones, with some cherts, outcrops a mile below the mouth of Fourth of July creek (see map, figure 2), and continues down the river for some 2 miles, to where it passes underneath the Mesozoic. The same belt probably extends westward and was observed again on the lower part of Washington creek, where it is represented chiefly by quartzites and tuffs.

[73] J. E. Spurr: The geology of the Yukon gold district. Eighteenth Annual Report, U. S. Geological Survey, part III, pp. 155-168.

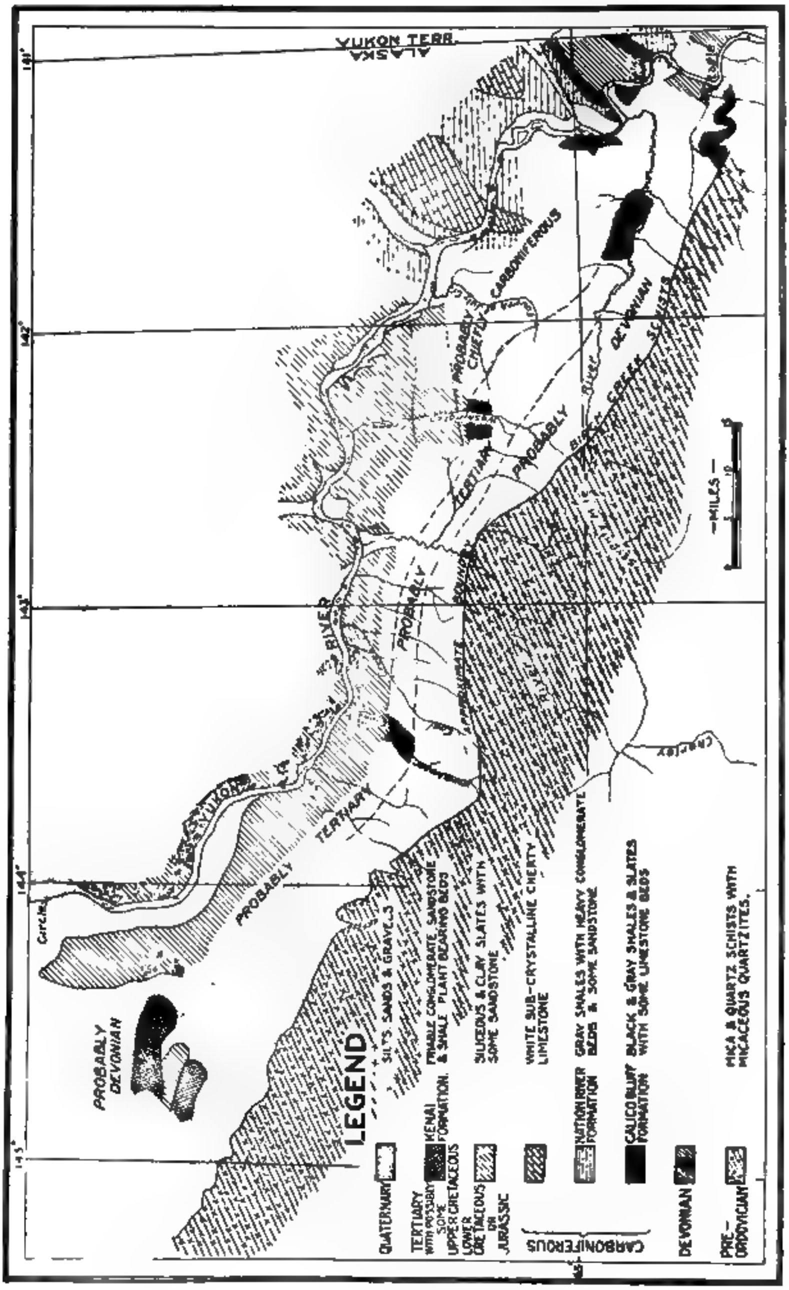

FIGURE 2.—*Geologic Map of Upper Yukon, Alaska*

By Alfred H. Brooks and E. M. Kindle

Devonian limestones were found at intervals along the river between the mouth of Coal creek and for some 3 miles below the mouth of Woodchopper. This limestone occurs interlarded among large masses of greenstone, which latter must also find place in the Devonian.

An entirely distinct belt of rocks, here also provisionally assigned to the Devonian, is exposed in a series of cliffs skirting the south bank of the river some 8 miles below Woodchopper creek. This belt includes massive limestones, thin-bedded limestones, shales, slates, and quartzites, with a little tuff. Mesozoic beds cut off this series from another belt of Devonian rocks, made up chiefly of greenstones, with some slate and chert, which continues to outcrop down the river nearly to Circle.

The shales of the Eagle belt and the limestones of the Washington Creek belts, as well as those interlarded with the greenstones at Woodchopper creek, carry fossils assigned to the Middle or Upper Devonian. The limestone and slate series outcropping 8 miles below Woodchopper creek yielded only a few fragmental fossils which have been assigned to the Devonian. On general stratigraphic grounds the latter series is considered the oldest, and it is not impossible that it may be in part, at least, Silurian.

This last group, here considered, the oldest Devonian rocks, though it may be of Silurian age, is exposed in a series of bold bluffs which mark the southwestern bank of the river for a distance of 3 to 4 miles. The strikes are about east and west and at right angles to the course of the river. Close folding, shearing, and faulting have obscured the structure, and the dips are varied, but most often to the north at angles varying from 45 to 60 degrees.

At the southern end of the section is a group of rock pinnacles made up for the most part of a massive blue to white, semicrystalline, exceedingly cherty limestone. Some shales occur with the limestones and some of the limestone layers are so siliceous as to be better described as cherts. This limestone has been much sheared and altered and all traces of bedding obliterated, and it was impossible to determine the thickness, which probably does not exceed a few hundred feet. In general it seems to strike about east and west, parallel to the rest of the series. Diligent search was rewarded by the finding of only a few fragmental fossils, including *Favosites* sp. and *Atrypa reticularis,* and it is on the basis of these indecisive fossils that the entire succession is provisionally referred to the Devonian. To the north of the limestone, and probably stratigraphically above it, is a mass of black shale and chert, and then an anticlinal fold appears to bring up the same limestone again. North of this fold there is a monotonous repetition of dark flaggy limestones, green clay

shales and slates, with some quartzites and a little tuff. All these rocks are closely folded and sometimes faulted, and there are probably duplications of the same beds. Therefore, though these rocks outcrop for several miles, they may not exceed a few thousand feet in thickness. The absence of greenstones, with the exceptions of a very subordinate amount of tuff, differentiates these rocks from the other Devonian terrains of the adjacent regions. In general the succession can be said to be calcareous and argillaceous with a striking absence of igneous and fragmental material. This succession is sufficiently distinctive to warrant giving it a formation name, were it not that its limits are too ill defined and its stratigraphic position too uncertain. In considering the age of the rocks, it should be noted that the oldest Devonian of the Porcupine is a limestone carrying Middle Devonian fossils, and that this rests on Silurian beds. If the series above described is Devonian, it represents a formation which is entirely lacking in the Porcupine section.

Some 2 or 3 miles below the mouth of Fourth of July creek a belt of limestones, cherts, with some interbedded carbonaceous clay shales and slates, together with considerable limestone conglomerates, are exposed on the west bank of the Yukon, which are here provisionally assigned to the Devonian without paleontologic evidence. The stratigraphic position of these rocks, like that of the series described above, is very uncertain. The lithologic character of these sediments would suggest that they belong with the cherty limestones, etcetera, already described and assigned to the oldest Devonian or Silurian, but their intimate association with igneous rocks points to a correlation with the limestone-greenstone series of Middle Devonian age to be described below.

The dominating rock of this belt is a blue cherty limestone which, adjacent to some intrusives, becomes quite crystalline. In places the limestone is interbanded with chert layers; in others, with beds of carbonaceous shales. Some beds of limestone conglomerate or breccias were found interlarded with the other sediments. In these the fragments are in part well rounded, suggesting water action; in part, quite angular, and may be frictional breccias. The cement of some of these conglomerates, which is iron stained, was believed in the field to be tufaceous, but a microscopic study of the thin-section shows it to be purely of sedimentary origin. Greenstone intrusives, chiefly of diabasic or basaltic character, are very extensively developed in association with these rocks. They occur chiefly as dikes, possibly also as sills. That the shearing which produced the limestone breccias was subsequent to the intrusives is shown by the fact that many of the dikes themselves are badly fractured and deformed. In places there are many calcite veins between the igneous rocks as well as

some of the quartz. The latter carry some pyrite. All of the rocks are characterized by an abundance of pyrite, whose oxidation products have stained them with iron. This pyrite is particularly abundant in the limestone, where it occurs in nodules and small seams.

The whole series is so closely folded that neither the structures or thickness could be determined. It seems probable that its thickness does not exceed 500 feet, but this is uncertain. The relation of these rocks to the adjacent formations was not determined, but they are probably separated from the Carboniferous to the east by a fault, and are overlaid unconformably on the north by the Mesozoic beds. Rocks of a similar character occur on Washington creek, about 15 miles west of the locality described above. The relations shown on the map (figure 2) indicate that the two areas are probably continuous. These rocks were first described by Collier,[74] who correlated them with Spurr's Rampart series. The observations of the writers indicate that they form a belt about 4 or 5 miles wide, striking about east and west and bounded both north and south by the younger Mesozoic beds. It should be noted, however, that mapping of the Mesozoic beds to the south is based on lithologic evidence alone.

This belt of Devonian is made up for the most part of very fine-grained sandstones and quartzites and argillites, with some limestone, together with large masses of greenstone, probably chiefly of a diabasic character. Interbedded with the true sediments are some fine-grained fragmental rocks, having a general greenish color. These, under the microscope, are seen to be made up of fine quartz grains with much calcite and chlorite. Collier called these rocks tuffs, and such they may be, though definite proof appears to be wanting. The greenstones are made up entirely of secondary minerals, in which quartz, calcite, and chlorite dominate. One thin-section revealed what seemed to be the remnants of an ophitic structure, and for this reason, and because of their general resemblance to the greenstones of the same province known to be diabases, these rocks are all assigned to the diabase family. All of these rocks are closely folded; the prevailing strikes are a little north of east, but there is no certainty of dip. They are unconformably overlaid on the north by Mesozoic beds.

The oldest Devonian rocks of the Yukon which have yielded fossils embrace a series of blue and white semicrystalline limestones which are exposed at intervals along the river for 15 to 20 miles below Coal creek. These limestone masses are separated by extensive areas of greenstone, which in turn are locally associated with some cherts and slates. The lime-

[74] Arthur J. Collier: The coal resources of the Yukon. Bulletin no. 218, U. S. Geological Survey, pp. 28-29.

stones probably form the base of this succession, as will be shown below. Its fossils are correlated with those from a limestone of Middle Devonian age on the Porcupine. The igneous rocks and associated slates and cherts are undoubtedly Devonian and in general younger than the limestones. They may belong either to the Middle Devonian or represent the Upper Devonian shale series found near Eagle and to be described below. It should be noted that heavy cherty limestone and associated rocks, which are traversed by the Yukon a few miles below Woodchopper creek and have been already described and provisionally assigned to the lowest Devonian or Silurian, occur in this same general area.

The limestones of this series occur in small patches, often representing small anticlines and apparently inclosed within the greenstone. It is essentially a blue cherty limestone, but locally has been altered to a semicrystalline phase, apparently due to the metamorphic effect of igneous rocks. On the lower part of Woodchopper creek and at a few other localities black argillites are associated with the limestones. The limestone was found only in the northern part of the area within a few miles above and below the mouth of Woodchopper creek. In the northern two-thirds of the area only igneous rocks were observed, with the exception of some small belts of red and green siliceous slates and cherts which occur within the greenstones.

The igneous rocks which make up this complex have been fully described by Spurr,[75] and it is not intended to go into the matter here. They appear to be in a large measure effusive rocks, but intrusives are not uncommon. In general, both the extrusive and intrusive phases are of basaltic or diabasic character, but they vary greatly in composition. Bedded tufaceous rocks are not uncommon, and some of these appear to grade into impure sediments.

In the hand specimens the rocks are characterized throughout by a green color. They are usually jointed and sometimes locally schistose. At several localities some coarse volcanic breccias were observed. The anticlinal structure of some of the limestone masses occurring in this complex has already been referred to, and beyond this there is little to be said of the altitude of the sediments. The igneous material is usually quite massive, though there is an occasional suggestion of different lava flows among the effusives and bedding among the tufaceous rocks, and marked jointing was noted throughout the greenstone series, producing blocky angular fragments.

The igneous series has a marked effect on the topography: where it

[75] J. E. Spurr: The geology of the Yukon gold district, Alaska. Eighteenth Annual Report, U. S. Geological Survey, part III, pp. 161-166.

forms the country rock, as in the Yukon as well as the larger confluent stream, the river valleys are narrow, with walls rising steeply from close to the water's edge. The smaller tributaries occupy V-shaped gorges. Many small castellated peaks and pinnacles break the contour of the valley slope, giving an irregular topography along the watercourses. This irregularity is not carried back into the interstream areas because of the general beveling to which the uplands have been subjected in a previous cycle.

Fossils were found at a number of localities in the limestones. At some exposures opposite the mouth of Woodchopper creek and about 1 mile farther up the Yukon the following fauna occurs in limestones interbedded with tuffs:

Devonian Fossils obtained near Woodchopper[76]

Cyathophyllum sp.	*Anoplotheca ? concava* (Hall).
Crinoid stems.	*Dalmanella* sp.
Stropheodonta cf. *calvini* Miller.	*Spirifer* sp.
Camarotœchia, small sp.	*Rensselæria ?* sp.
Atrypa reticularis Linn.	*Cypricardinia* sp.
Atrypa cf. *flabellata* Goldf.	*Conocardium* sp.
Schizophoria striatula (Schlotheim).	*Actinopteria* near *perstrialis* Hall.
Ambocœlia cf. *umbonata* (Conrad).	*Pleurotomaria* sp.
	Sigaretus ? n. sp.

This is the same fauna and horizon as that occurring at the mouth of Salmontrout river on the Porcupine (see page 327). *Atrypa* cf. *flabellata* is one of the most abundant species in both faunas. The very peculiar gasteropod here referred doubtfully to *Sigaretus* and *Stropheodonta* cf. *calvini* are also common to both.

About 2 miles below Woodchopper creek the igneous beds which are there the predominant rocks are interrupted by a cliff of bluish gray Devonian limestone rising 200 feet above the river. Fossils are very scarce here. The following species were obtained:

Crinoid stems.	*Stropheodonta* sp.
Atrypa reticularis.	*Conocardium* sp.
Camarotœchia sp.	

The base of the Devonian section is not exposed on the Yukon, but the limestone on the Porcupine, which the faunas pretty clearly indicate to be the stratigraphic equivalent of the limestone beds near Woodchopper, is known to rest directly on the Silurian. Both of these faunas appear to

[76] It is proposed to describe fully and to illustrate the Devonian and Silurian faunas listed in this paper in a subsequent paper, when the paleontologic determinations will be subject to revision, with the aid of more complete collections.

be referable to the Middle Devonian, as pointed out in the discussion of the Porcupine fauna (see page 328). Unless, therefore, the Devonian section begins earlier on the Yukon than on the Porcupine, of which there is no positive evidence, the limestones near Woodchopper lie near the base of the Devonian section. Their Middle Devonian age is suggestive of an unconformity at their base.

While this evidence points to the Middle Devonian age of the limestones associated with the greenstones, the greenstones may be somewhat younger, and represent about the same horizon as the Upper Devonian shales and slates to be described as occurring between Eagle and Calico bluff. If this proves to be the case, it would indicate that while igneous activity was widely spread, yet the resulting extravasations were comparatively local.

It is worthy of note that rocks of a similar diabasic composition have been described by McConnell[77] as occurring along the Yukon near Dawson and called by him the "Moose Hide group." McConnell shows that this rock is greatly sheared and in part altered to serpentine. The observations of the writers indicate that this same terrain forms the greater part of the country rock along the Yukon from Dawson to the mouth of Fortymile river.

Spurr's type locality for the igneous rocks included in the Rampart series is along the Yukon below the Flats in the so-called Ramparts. Though this area was not studied in detail by the writers, yet the same types of rocks are known to occur as those described on the upper river. Unfortunately there have been no fossils found in the Ramparts of the Yukon and the correlations depend on the general lithologic similarity.

Mendenhall[78] has described an igneous complex under the name Kanuts series, which occupies an area of several hundred square miles between the Ramparts of the Yukon and the Koyukuk valley. This complex is made of basic igneous rocks, including both effusive and extrusive, together with some pyroclastics and hornstones. Mendenhall points out the similarity of these rocks to Spurr's Rampart series and provisionally assigns them to the Middle Paleozoic.

In the region south of the Ramparts there are many greenstones[79] in association with various types of sediments which have been assigned to the Devonian. These greenstones are of diabasic character and include

[77] R. G. McConnell: The Klondike gold fields. Geological Survey of Canada, no. 884, 1904, pp. 22B-23B.

[78] Walter G. Mendenhall: A reconnaissance from Fort Hamlin to Kotzebue sound. Professional paper no. 10, U. S. Geological Survey, pp. 32-38.

[79] L. M. Prindle and Frank L. Hess: The Rampart gold placer region. Bulletin no. 280, U. S. Geological Survey.

some pyroclastics and are similar to those of the upper Yukon, with which they may be provisionally correlated.

The Devonian of the Rampart region has been recently described by Prindle,[80] and he has recognized two subdivisions under this heading: (1) A lower, which may be Silurian, made up chiefly of cherts, argillites, and greenstones, and (2) an upper or true Devonian, consisting of massive limestones, greenstones, red, green, and black argillites, quartzites, and conglomerates. The limestones carry fossils, assigned to the Middle Devonian. Of these terrains it is probably safe to say that they represent in a general way the igneous group of the upper Yukon, though close correlations can not now be made.

Devonian limestone has been found in the Mount McKinley region and in the middle Kuskokwim[81] valley. Keele has described some limestones, quartzites, and slates which outcrop in extensive areas in the upper part of the Stewart River[82] basin and assigned them to the Devonian. The evidence that this series is Devonian would appear to be far from conclusive, but it can hardly be questioned that they are Paleozoic. In a personal letter Mr Keele presents a measured section of these rocks which shows a greenish quartzite (450 feet) at the bottom, succeeded by over 3,000 feet of argillites, with some arenaceous and calcareous rocks, and then overlaid by some 600 feet of sandstones, grits, and fine conglomerates. The whole section measures about 4,200 feet. Their succession does not bear much resemblance to any of the rocks of the Upper Alaska-Yukon section, but it is not unlike some of the terrains of the Rampart district which have been provisionally assigned to the Devonian.

In the region north of the Yukon Devonian terrains have not been definitely recognized, but fossils found in the alluvium point to the presence of Devonian rocks in the area drained by the Chandlar river.[83]

The Devonian fauna which has been described from the Mackenzie River district by Meek[84] and Whiteaves[85] represents apparently about the same general horizon as the lowest Devonian limestone fauna on the Porcupine and Yukon, but there are comparatively few species common to the two. No Lower Devonian fauna has been reported from the Mac-

[80] L. M. Prindle: The Fairbanks and Rampart quadrangles. Bulletin no. 327, U. S. Geological Survey.

[81] J. E. Spurr: A reconnaissance in southwestern Alaska. Twentieth Annual Report, U. S. Geological Survey, part vii, pp. 157-159.

[82] J. Keele: Report on the Upper Stewart River region, Yukon. Geological Survey of Canada, no. 943, 1906, Ottawa, p. 14C.

[83] F. C. Schrader: A reconnaissance along the Chandlar and Koyukuk rivers. Twenty-first Annual Report, U. S. Geological Survey, part ii, p. 476.

[84] Transactions of the Chicago Academy of Science, vol. 1, 1869, pp. 61-114, pls. 11-15.

[85] Geological Survey of Canada, Contributions to Paleontology, vol. 1, part 3, 1891, pp. 197-253, pls. 27-32.

kenzie River district, although "2,000 feet or more of grayish limestone interstratified with dolomites," lying below the beds with Middle Devonian fossils, are referred provisionally to the Devonian by McConnell.[86] In the absence of paleontologic evidence of the age of this dolomitic series, it would appear probable that it is of Silurian age and should be correlated with a series of somewhat similar character on the Porcupine river which is shown to be of Silurian age in this paper.

In southeastern Alaska Lower, Middle, and Upper Devonian faunas have been recognized by Kindle.[87] Neither the faunas nor the lithologic members of the section show any close resemblance, however, to those of the Upper Yukon Devonian section.

The slates and shales, with subordinate sandstone masses and some greenstones, which outcrop along the Yukon between Eagle and Calico bluff, form a second group of Devonian rocks. The upper part of this succession, made up of black shale and slate, lies immediately underneath and conformable to the limestones and shales of the Calico Bluff formation of Lower Carboniferous age. It is probable, therefore, that all of the rocks in this group should be referred to the Upper Devonian. The few fossils which have been found in the rocks of this group bear out this point of view.

Immediately northwest of the town of Eagle is a high ridge trending about east and west. Eagle peak, the eastern end of this ridge, is made up largely of greenstone, which outcrops in numerous small cliffs along the slope. The greenstone is both massive and schistose, the latter phase occurring along shear zones. The massive form, which was studied by Prindle a few miles to the westward, appears to be a basalt in which the schistose phases are made up entirely of secondary minerals, among which chlorite dominates. At this locality no tuffs were found, but Prindle reports some tufaceous rocks near the International boundary on what appears to be an eastern extension of this belt.

On the southern slope of Eagle peak, and half way between the river and the summit, a bed of shaly siliceous limestone, less than a hundred feet thick, was observed, and Prindle reports similar occurrences a few miles to the westward. The presence of this unaltered limestone in the midst of the igneous rock indicates that the latter were surface flows rather than intrusions, and suggests that the volcanic outpourings were submarine rather than terrestrial.

The section exposed along the river, on the other hand, about 1,500

[86] Geological Survey of Canada, Contributions to Paleontology, vol. 1, part 3, 1891, p. 250.

[87] Journal of Geology, vol. 15, 1907, pp. 324-330.

feet below the limestone described, shows a series of slates and phyllites intimately intermingled with greenstones, some of which may be intrusive, but all appear to be of the same types as those described above. These rocks are intensely folded and shattered. It is not impossible that these phyllites may represent a part of the older schist series, but their association with the Devonian is so intimate as to lead to their assignment to that system. These phyllites and some greenstones are exposed for about a mile down the river, and then, after passing a belt without any exposures, an area of black and gray shales with some feldspathic sandstones is encountered. These beds are thrown up into broad, open folds striking about east and west, with dips of from 20 to 50 degrees. Careful search was rewarded by only a few fossils, but sufficient to identify the beds as Devonian. It must be confessed that the evidence that the greenstones, with associated limestones and phyllites, belong to the same terrains as the shales and sandstones is by no means conclusive. Similar greenstones, however, in the other parts of the province are known to be of Devonian age.

Near the big bend 6 miles below Eagle (see map, figure 2), a belt of chert conglomerate and sandstone, with some shale, here assigned to the Carboniferous, crosses the river. These rocks are here correlated with the Nation River formation, but it is not impossible that they may be of Devonian age, in which case they represent a phase of the Devonian unknown in any other part of the section here described, or may even be of Tertiary age. The relation of these Devonian shales to this conglomerate series could not be determined, but the general distribution of the two formations suggests that they are separated by a fault. Half a mile below the last outcrop of the conglomerate there is a second belt of Devonian, here made of black siliceous slates carrying considerable pyrite, succeeded by black clay shales and slates. These carry a few Devonian fossils and merge upward into a shale limestone series which yielded Carboniferous (Mississippian) invertebrates and here called the Calico Bluff formation. The shales of this Upper Devonian horizon have a rather uniform dip downstream, with a thickness of at least 1,000 feet. The lower and more siliceous beds of this horizon are much jointed, two systems being recognizable, one parallel and one at right angles to bedding. A diabase dike was noted cutting these slates at right angles to the bedding.

Fossils are extremely rare in the shale series which forms the highest divisions of the Devonian. Below Eagle about 5 miles, on the west bank of the Yukon, a single specimen of a lamelli-branch was found in the drab-colored Upper Devonian shales. Although fragmentary, it appears

almost certainly to belong to the species *Buchiola retrostriata,* an Upper Devonian form very characteristic of the Nunda or Portage in the New York section. The shales in which it was found resemble those of the Nunda.

These drab shales are followed above by black shales in the section as developed between Eagle and Calico bluff. The black shales, which sometimes are altered to slate, are well exposed in the northeast bank of the Yukon one-half mile above Calico bluff. Here a small Lingula somewhat like *L. spatulata* occurs sparingly. No other fossils were found in the black shale at this place. The same beds form the base of the Calico Bluff section where their relation to the Carboniferous series is clearly shown. The section exposed at Calico bluff is given below in order to show in detail the transition of the Carboniferous series:

Calico Bluff Section

		Feet
o.	Gray to blackish shale, with few bands of limestone	300
n.	Gray limestone in 6-inch to 12-inch bands, interbedded with thin bands of black shale	500
m.	Black shale and subordinate thin bands of limestone	60
l.	Black carbonaceous shale	50
k.	Gray chert and black shale	6
j.	Dark gray limestone full of Productus, etcetera	9
i.	Dark carbonaceous shale	20
h.	Gray cherty limestone	25
g.	Soft fissile black shale	55
f.	Gray chert	8
e.	Fissile black carbonaceous shale	150
d.	Black carbonaceous shale, with slaty cleavage developed in most beds	100
c.	Black carbonaceous shales, with some thin black chert bands interbedded	40
b.	Black cherts in 4-inch to 6-inch bands and interbedded black shale	55
a.	Black carbonaceous fissile shale	150
	Total	1528

The only fossils found in the lower 500 feet of this section is a small Lingula somewhat like *L. spatulata,* but a different species. In number *i* of the section occurs a *Leiorhynchus* closely allied to *L. laura* Billings and a *Chonetes* somewhat resembling *C. manitobensis.* Characteristic Lower Carboniferous fossils appear in the section in the divisions above *g*.

While the Devonian age of the beds below number *h* can hardly be positively affirmed from the evidence of the three species found in them, the entire absence of characteristic Carboniferous fossils from this portion of the section and the still lower drab and reddish shales seen elsewhere is

significant, and, taken together with the character of the few fossils occurring in it, justifies us in referring the lower 500 feet of the Calico Bluff section or the portion below the lowest limestone bands to the Devonian with considerable assurance. Above number *g* of the section the beds hold a Carboniferous fauna.

The above rather fragmentary data clearly show both an extensive development and a wide distribution of rocks assignable to the Devonian in the Upper Yukon basin. If one were to venture on a subdivision of this great series on the facts in hand, it would be to recognize three general groups. The lowest group would comprise the heavy cherty bluish white limestones and associated argillites, quartzites, and thin-bedded limestones occurring below Woodchopper creek, which may be Silurian and are characterized by a relatively small amount of igneous material. The cherts, quartzites, and limestones of the Washington Creek area are provisionally included with the formation. The lowest member of the Devonian or Upper Silurian described by Prindle in the Rampart region, and probably also the rocks of the Stewart river, assigned to the Devonian by Keele, can be provisionally correlated with this general horizon.

A second group would include limestones and the associated igneous rocks, argillites, and cherts. The igneous rocks of this group would appear to be identical with Spurr's Rampart series; but it must be remembered that it is only for the limestone member of this group that the age has been determined, and that the igneous rocks may be somewhat younger. In its typical occurrence this igneous group is undoubtedly the best defined of the stratigraphic subdivisions here proposed for the Devonian. As a cartographic unit, however, it is not serviceable, because including, as it does, some intrusives, these are likely to be found as dikes cross-cutting various older formations. Moreover, the equivalent of this igneous complex in adjacent areas may be found among the purely sedimentary rocks. The stratigraphic relations of Middle Devonian horizon to the older rocks here assigned to the Devonian is not known, but may very likely be one of unconformity.

The third group includes the argillites and subordinate sandstones and siliceous slates, which occur immediately underneath and conformable to Mississippian terrains. These rocks are but sparingly fossiliferous, and may be found to be in part of synchronous age with the igneous complex of the second group. If the argillite group is distinct from the igneous group, there may be an unconformity between the two, and the apparent absence of the latter in many localities may be due to erosion, which removed the igneous rocks before the sediments were laid down.

Little can be said of the thickness of the Devonian in this province.

The heavy limestones and associated rocks of the lowest group may measure several thousand feet. It is probably safe to estimate that the exposures along the upper Yukon of Middle Devonian limestones and associated greenstones indicate a thickness of from 5,000 to 8,000 feet, much the larger part of which is made up of igneous rocks. The upper argillites and associated sandstones are roughly estimated to have a thickness of about 1,000 feet.

The Devonian fauna of Alaska seems, so far as we know it, to conform to a general and widespread tendency of the Devonian fauna to develop provincial types. Neither in Alaska nor elsewhere do we know any type of Devonian fauna with such a worldwide distribution as the Middle Silurian fauna, with which the Porcupine Silurian fauna has been correlated in preceding pages. Very diverse types of faunas were developed during the Devonian period, which sometimes flourished even in such close proximity as contiguous portions of the same sea. It is not surprising, therefore, to find strong contrasts between the fauna of the Devonian limestone of the Yukon section and that representing a similar horizon in southeastern Alaska. The latter also appears to bear little resemblance in its composition to the best known of the Rocky Mountain Devonian faunas, the fauna of Nevada,[88] or the Jefferson[89] limestones.

The marine basin represented by these limestones appears to have had a considerable north and south extension, reaching from central Nevada into western Montana; but it was probably not connected with the southeastern Alaskan basin, since the Middle Devonian fauna of the latter region appears to have a closer relationship to the Devonian of the Manitoba than that of the Rocky Mountain region.

The southeast Alaskan and the Manitoba faunas contain foreign elements which are unknown in Devonian faunas of north or eastern America. The presence in southeast Alaska of *Hercynella*[90] and in Manitoba of *Stringocephalus*,[91] genera which are well known in Europe, but unknown in eastern America, indicates both the relationship of these western faunas to those of Europe and a probable northwesterly route of intermigration between the Devonian faunas of western America and Europe.

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[88] C. D. Walcott: Paleontology of the Eureka district. Monograph no. viii, U. S. Geological Survey, 1884, pp. 99-211, pls. 2-6, 13-18.

[89] E. M. Kindle: The fauna and stratigraphy of the Jefferson limestone in the northern Rocky mountains. Bulletin no. —, U. S. Geological Survey, 1908. (In preparation.)

[90] E. M. Kindle: Notes on the Paleozoic faunas of southeastern Alaska. Journal of Geology, vol. xv, 1907, p. 326.

[91] J. F. Whiteaves: Descriptions of some new or previously unrecorded species of fossils from the Devonian rocks of Manitoba. Transactions of the Royal Society of Canada, vol. viii, 1890, section iv, p. 93.

With our present knowledge of the Middle Devonian fauna of the Yukon section, a very close relationship to other faunas can not be pointed out. It appears probable, however, that the Devonian fauna of the Yukon River district bears a closer relationship to the Mackenzie River fauna[92] than to any of the other western faunas outside of Alaska.

The known Upper Devonian fauna of the Yukon section, limited as it is to a very few species, is too imperfectly known to afford much basis for comparison with faunas elsewhere. The presence in it, however, of *Lieorhynchus* and a *Buchiola* closely allied to if not identical with *retrostriata* suggests that a more complete knowledge of it will show a rather close relationship with the Upper Devonian of eastern America. None of the species occurring in the Upper Devonian of the Yukon section have been thus far found in the Upper Devonian of southeastern Alaska.

CARBONIFEROUS

The Devonian rocks are not separated by any break from the overlying Carboniferous terrains. The division line between the two systems lies within the upward extension of the black argillites, which form the uppermost member of the Devonian. As there is no abrupt change in lithologic character in passing from one group to the other, the line of cleavage between the Carboniferous and Devonian must be determined largely on paleontologic evidence. This is as would be expected, for both the uppermost part of the Devonian and the lowest member of the Carboniferous are represented by sediments that are deposits of deep-sea conditions.

The Carboniferous terrains of the upper Yukon include about 5,000 feet of strata, the lowest of which rest conformably on the Devonian. A triple subdivision has been recognized, the two lowest of which form well defined stratigraphic units and have been given formation names, while the upper, which is to be correlated with so-called "Permian" of Alaska, has not been named, because its limits are not well defined. The large collections made from the highest member by the writers are referred by Doctor Girty to the Upper Carboniferous and not to the Permian, as has been done with other collections from this locality by previous investiga-

[92] F. B. Meek: Remarks on the geology of the valley of the Mackenzie river, with figures and descriptions of fossils from that region, in the Museum of the Smithsonian Institution, chiefly collected by the late Robert Kennicott, Esq. Transactions of the Chicago Academy of Science, vol. 1, 1869, pp. 61-114, pls. xi-xv.

J. F. Whiteaves: The fossils of the Devonian rocks of the Mackenzie River basin. Contributions to Canadian Paleontology, vols. 1 and iii, 1891, pp. 197-253, pls. 27-32.

tors. It will be shown that a small fauna collected from the highest bed in this Upper Carboniferous has certain affiliations with the Mesozoic, which would go to show that the Carboniferous section of the Yukon is complete from the Devonian to the Mesozoic.

The lower of the two well defined formations, for which the name "Calico Bluff" is proposed, embraces about 900 feet of black and gray shales, with some slate and numerous interpolated thin beds of limestone. The whole formation carries an abundant fauna, assigned to the Mississippian by Dr George H. Girty. Its typical exposure is at Calico bluff, on the Yukon, about 15 miles below Eagle (see map, figure 2). The Calico Bluff formation is separated by an unconformity from the succeeding formation, here called the "Nation River." There can be little doubt of this unconformable relation, though no complete section was found showing both. The relations are inferred from the apparently abrupt change in character of sediments to fine limestone from coarse fragmental material. It is not improbable, however, that detailed mapping may reveal a considerable thickness of strata lying between Calico bluff and Nation river, as here described. Whether such strata, if found, should be included in one or the other of these formations, or be mapped as a distinct stratigraphic unit, must be left to the future to determine.

As shown by the detailed section on a preceding page, the physical changes involved in the transition from Devonian to Carboniferous sedimentation embraced a continuation of the deposition of shale-producing sediments interrupted at intervals by periods of limestone deposition. The Carboniferous fauna seems to have made its first appearance in the region with the advent of limestone-forming conditions, during the temporary cessation of the deposition of black shale sediments. The regular and frequent alternations of closely folded, light colored limestone and dark shale, which characterize the Carboniferous portion of the nearly vertical face of Calico bluff, give it an unusual and striking appearance, as seen from the river (see plates 18 and 19).

The Carboniferous fossils obtained here were submitted to Dr George H. Girty, who reports the following species from bed 9*j* of the section (see page 288), which is the lowest bed holding Carboniferous fossils:

Fossils from Bed 9j Calico Bluff

Fenestella sp.	*Productus* aff. *biseriatus* Hall.
Polypora sp.	*Productus* sp.
Cystodictya sp.	*Spirifer* aff. *bisulcatus* Sowerby.
Stenopora ? sp.	*Spirifer* aff. *keokuk* Hall.
Rhombopora sp.	*Spirifer* sp.
Derbya ? sp.	*Reticularia* aff. *setigera* Hall.

UPPER END OF CALICO BLUFF, YUKON RIVER

Showing Calico Bluff limestones and shales. Photograph by C. L. Andrews

Chonetes aff. *choctawensis* Girty.
Productus aff. *cherokeeensis* Drake.
Productus aff. *inflatus* McChesney.
Productus aff. ? *hirsutiformis* Walcott.
Productus aff. *punctatus* Martin.
Productus aff. *setiger* Hall.
Martinia ? sp.
Leiorhynchus sp.
Aviculipecten sp.
Myalina sp.
Macrodon aff. *carbonarius* Cox.
Bellerophon sp.
Phillipsia sp.

From the black shale above this fauna, in division *l* of the section, a small fauna was secured containing three species, reported by Girty as follows:

Leiorhynchus aff. *mesicostale* Hall.
Goniatites undet.
Orthoceras sp.

The *Leiorhynchus* of this fauna is a recurrence of the species found in bed *g* of the section, which is referred to the Devonian. It is characteristic of some of the species of this genus in the New York Devonian to be associated with black shales at various horizons in a section, while they are entirely absent from the intervening sediments.

The following species have been recognized from the several beds from *j* to *n* of the Calico Bluff section by Doctor Girty which were not included in the fauna of division *j*.

Fossils from Beds 9j to 9n, Calico Bluff

Zaphrentis sp.
Archæocidaris sp.
Fenestella sp.
Pinnatopora sp.
Polypora sp.
Rhombopora sp.
Cystodictya sp.
Stenopora sp.
Stenopora ? sp.
Schizophoria sp.
Chonetes sp.
Chonetes aff. *choctawensis* Girty.
Productus aff. *biseriatus* Hall.
Productus aff. *semireticulatus* Martin.
Productus aff. *hirsutiformis* Walcott.
Productus aff. *parvus* Meek and Worthen.
Productus aff. *cherokeeensis* Drake.
Productus aff. *cora* D'Orbigny.
Productus 2 spp.
Spirifer aff. *bisulcatus* Sowerby.
Spirifer aff. *keokuk* Hall.
Reticularia aff. *setigera* Hall.
Ambocœlia ? sp.
Camarotœchia ? sp.
Camarophoria sp.
Aviculipecten sp.
Macrodon n. sp.
Pleorophorus aff. *subcostatus* Meek and Worthen.
Pleorophorus sp.
Chiton sp.
Trachydomia ? sp.
Pleurotomaria 3 spp.

Doctor Girty makes the following statements[93] regarding the horizon represented by the Carboniferous of Calico bluff and other sections representing a similar horizon:

[93] Manuscript report to the writers.

"I have been unable to trace the affinity of this fauna with a member of the Russian section, but presumably it is somewhere near the age of the *Productus giganteus* zone, in which case a gap of considerable extent separates this from the Upper Carboniferous fauna described below. The fauna of the Calico Bluff section appears to be related to that of the upper part of the Mississippian section as developed to the south and west of the typical area. I refer to the Spring Creek limestone and Marshall shale of Arkansas and the Caney shale of Indian Territory (and probably the Eureka shale of Nevada), which from available data appear to represent the upper portion of the typical Mississippian section. This relationship of the Alaskan fauna I believe to be a real and not a fancied one, and while belonging distinctly with the faunas just mentioned, rather than with the typical Osage and Kinderhook, it would at present be unsafe to say that these localities represent the upper Mississippian alone."

Since the preceding observations of Doctor Girty indicate that the nearest faunal equivalents of the Calico Bluff fauna in the United States are representatives of the upper portion of the Mississippian section, it should be pointed out that all of the available stratigraphic evidence indicates that it is the earliest Carboniferous fauna present in the Yukon section. The stratigraphic evidence appears to place it somewhat lower than the faunal evidence and to indicate that it represents both the upper and the lower portions of the Mississippian section.

A section about 2 miles above the mouth of Seventymile river, on the opposite bank of the Yukon, exposes the Carboniferous series seen at Calico bluff and some higher beds which show the Lower Carboniferous shales terminated by a coarse conglomerate which, with some interbedded shales, is about 200 feet thick. This conglomerate may represent the base of the Nation River series. The limestones and shales here show about the same association of species as in the Calico Bluff section.

The Nation River series includes about 3,700 feet of gray clay shales, with some clay slates interpolated with heavy beds of conglomerate and some sandstone. It is typically exposed along Nation river, where it includes some small seams of bituminous coal. The limits of this formation are well defined. The base is believed to be marked by an unconformity which separates it from the shales and limestone of the Calico Bluff formation. At the top it is limited by the heavy limestone which previously formed the topmost member of the Carboniferous and will be described below.

Two conglomerate beds are particularly striking in this formation. One occurs at the base and is very massive, and the second, which is not quite as heavy, occurs about 1,000 feet above the base. The succeeding thousand feet is largely made up of shales, with some fine conglomerates and sandstone, while the upper 500 feet of the formation is chiefly gray shales. Some bituminous coal beds occur in the lower part of the section.

The Nation River formation has yielded no fossils except a few plant fragments, upon which Mr David White has reported as follows:

"This collection consists of three fragments of rock with one counterpart containing small fragments of carbonized wood, decorticated stems, etc. The plant remains bear evidence of transportation, maceration, and trituration, the result being that none of them are definitely determinable, even generically. One fragment, about 1 c. m. in length and 6 mm. in width, evidently represents a branch of some lepidophyte or gymnosperm. Although it is partially decorticated as the result of maceration, so that the epidermal characters are lost, the subepidermal features of this branch so closely resemble those of certain Carboniferous strobiliar axes and earlier types of phyllotaxy that I am inclined to regard it as probably belonging to one of these Paleozoic forms. In fact, though constrained to emphasize the poor condition and limited characters presented by the specimen and the consequent hazard of any attempt at identification, I am nevertheless disposed to regard this fragment as belonging to one of the Carboniferous lepidophytes. Among the latter it bears the closest resemblance to some of the early forms in the basal Carboniferous or the late Devonian."

The stratigraphy and the invertebrate faunas of the associated formations strongly support the opinion that the Nation River coal is of Carboniferous age. The coal seam occurs near the axis of an anticline, the beds dipping away in opposite directions at angles of 30 to 60 degrees on the north and south sides of the Nation River valley. South of the river they pass under a massive white limestone carrying an Upper Carboniferous fauna and in which a series of open folds is developed along the north side of the Yukon. Considerable interest attaches to the beds at the Nation River coal mine, because it is the only locality in the Yukon basin where beds of Carboniferous age have afforded coal.

The uppermost member of the Carboniferous is a white subcrystalline limestone, with a minimum thickness of at least 200 feet, which carries fossils assigned by Doctor Girty to the Upper Carboniferous. This terrain was first assigned to the Upper Carboniferous by Schuchert,[94] and later placed in the Permian[95] on the basis of more complete collections. It will be shown below that they have been correlated with the so-called Permian rocks of southeastern Alaska and White and Copper rivers; but, though Doctor Girty is inclined to accept this correlation, he believes that they should all be called Upper Carboniferous rather than Permian.

[94] J. E. Spurr: Geology of the Yukon gold district. Eighteenth Annual Report, part III, p. 170.

[95] Arthur J. Collier: Coal resources of the Yukon. Bulletin no. 218, U. S. Geological Survey, p. 16.

Alfred H. Brooks: The geography and geology of Alaska. Professional paper no. 45, U. S. Geological Survey, pp. 222-223.

It has not seemed desirable to give this limestone horizon a formation name, because on the Yukon its limits were not definitely determined and, moreover, its type locality is probably to be sought in southeastern Alaska. The Upper Carboniferous limestone is typically exposed in some large open folds, accompanied by more or less faulting, along the north side of the Yukon for some 3 or 4 miles above Nation river. The same horizon was identified about 30 miles below, on the south side of the river and just west of the mouth of Coal creek. Here it is exposed in a small area closely associated with some pyroclastic material similar in every way to that occurring with the Devonian rock. Were not the paleontologic evidence in regard to this occurrence conclusive, this limestone would have been placed with the Devonian. The occurrence, however, goes to prove that there was some igneous activity during late Carboniferous time. It also suggests the possibility that some of the igneous rocks which have been mapped as Devonian may eventually prove to belong to the Carboniferous.

The fauna characterizing this highest Carboniferous limestone is shown in the following list of fossils determined by Doctor Girty:

"*Lot 14: Fossils from west Bank of Yukon, 1½ miles above Nation River*

Zaphrentis sp.
Stenopora sp.
Streptorhynchus aff. *S. pelargonatus* Schlot.
Chonetes aff. *morahensis* Waagen.
Productus aff. *horridus* Sowerby.
Productus aff. *aagardi* Toula.
Productus aff. *P. porrectus* Kut. ?
Productus aff. *mammatus* Keys.
Productus aff. *irginæ* Kut.
Productus aff. *koninckianus* Vern.
Productus sp.
Aulosteges sp.
Marginifera aff. *splendens* Norwood and Pratten.
Spirifer aff. *marcoui* Waagen.
Squamularia aff. *perplexa* McChesney.
Spiriferella arctica Houghton.
Cleiothyrodina n. sp.
Rhynchopora aff. *nikitini* Tschern.
Schizodus sp.
Aviculipecten sp.
Omphalotrochus sp.

"*Lot 15: Fossils from Limestone 1½ miles southeast of Mouth of Nation River*

Streptorhynchus aff. *S. pelargonatus* Schlotheim.
Productus aff. *aagardi* Toula.
Productus aff. *koninckianus* Vern.
Aulosteges sp.
Marginifera ? aff. *splendens* Norwood and Pratten.
Spiriferella arctica Houghton.

"*Lot 22: Fossils from south Bank of the Yukon below Glenn Creek*

Polypora sp.
Rhombopora sp.
Streptorhynchus aff. *pelargonatus* Schlotheim.
Productus aff. *transversalis* Tscherny.
Productus aff. *aagardi* Toula.
Spirifer aff. *cameratus* Tscherny. non Morton.
Spiriferella aff. *artiensis* Stuckenberg.
Spiriferella arctica Houghton.
Squamularia aff. *perplexa* McChesney.

Productus aff. *koninckianus* Vern.
Productus aff. *porrectus* Kut. ?
Marginifera ? aff. *splendens* Norwood and Pratten.
Camarophoria margaritovi Tschern.
Aviculipecten 2 spp.
Fish tooth.

"This fauna is unlike anything known in central and eastern North America, and appears to be rather closely allied to that of the Gschel-stufe of the Ural mountains. Probably the fauna of the Hueco, Weber, and Aubrey formations of western United States will be found more or less closely related. In Alaska it has been collected also in Pybus bay and on Kuiu island."

Lots 14 and 15 represent the limestone in its typical development, while the limestone which furnished lot 22 is associated with beds of igneous origin. The limestone, which is of Upper Carboniferous age, terminates the Paleozoic section in the Upper Yukon region. The succeeding strata in the section were not observed in direct superposition, but a series of argillites, with one or more limestone beds, is believed to hold this position. A collection of fossils was made in this series half a mile above the mouth of Nation river, from a limestone about 15 feet in thickness. A species of *Halobia* is the most abundant fossil in this collection. Dr T. W. Stanton refers the fauna provisionally to the Triassic. If this provisional determination is correct, the Upper Carboniferous limestone of the Yukon section is limited above by rocks of Triassic age.

The Carboniferous rocks above described show practically no metamorphism, and are in strong contrast in this respect to all the older rocks of the Yukon except the uppermost member of the Devonian. It is also noteworthy that, with the single exception of the pyroclastics found with the Upper Carboniferous limestone at Glenn creek, there is no evidence of igneous activity during the deposition of the Carboniferous sediments of the upper Yukon.

The Carboniferous terrains of the upper Yukon are thrown up into a series of broad, open folds, but some of the formations when studied in detail are found to have suffered intense cross-folding, which has resolved itself into many minor crenulations. This is beautifully shown in the cliffs of Calico bluff. Here a rock face nearly 1,000 feet high exposes the beautifully banded slates and limestones, which are intensely crumpled in a direction nearly at right angles to the axis of the anticline of which the bluff forms a western limb. The writers are indebted to Mr C. L. Andrews, of Eagle, for the accompanying photograph showing these crenulations (see plates 18 and 19).

Spurr[96] included in his stratigraphic column a group of gray lime-

[96] J. E. Spurr: Geology of the Yukon gold district. Eighteenth Annual Report, U. S. Geological Survey, part III, pp. 169-175.

stones, carbonaceous argillites, and conglomerates which he called the "Tahkandit series," and assigned to the Upper Carboniferous on the basis of Schuchert's determination of the fossils in the limestones. This group appears to comprise the three subdivisions of the Carboniferous which have been described above. The Tahkandit, as defined by Spurr, can therefore be regarded as the equivalent of the entire Carboniferous section of the Yukon.

Carboniferous rocks are known to occur in many widely separated localities in Alaska besides the upper Yukon valley. In but few of these have the studies gone into sufficient detail to permit of a subdivision into formations. In the Porcupine basin, in southeastern Alaska, in the headwater region of the Copper, Tanana, and White rivers, and at cape Lisburne, however, some of the details of the stratigraphic succession have been determined and certain correlations with the Yukon section can at least be suggested.

Along the Porcupine river the Lower Carboniferous section resembles the Calico Bluff formation, as seen along the Yukon, in being composed largely of interbedded shales and limestones, but differs from it in having a larger percentage of drab-colored shales, which are often arenaceous and tough instead of fissile and black (see page 331). The presence of this same Lower Carboniferous horizon in the region lying northwest of the Porcupine is indicated by a few fragmental fossils collected by S. J. Marsh[97] in the Endicott mountains near the Arctic divide, probably 20 or 30 miles west of the International boundary.

In 1899 Schrader collected some fossils from the gravels of the Chandlar River basin lying west of the Porcupine, which were provisionally referred to the Devonian,[98] but it has since been suggested by Doctor Girty[99] that they are of Lower Carboniferous age.

In the same northern Alaska region there is a crystalline limestone and clay shale horizon, called by Schrader[100] the "Lisburne," which has now found definite place in the Lower Carboniferous[101], though first placed in the Devonian. In the Anaktuvuk valley there is a conglomerate and quartzite series, called by Schrader[102] the "Stuver formation," lying beneath the Lisburne unconformably, which may be either Carboniferous

[97] The writers are indebted to Mr Marsh not only for these fossils, but also for notes on the geology and maps of the region explored by him.

[98] F. C. Schrader: A reconnaissance in the Chandlar and Koyukuk basins. Twenty-first Annual Report, U. S. Geological Survey, part ii, p. 476.

[99] Bulletin no. 278, U. S. Geological Survey, p. 26.

[100] F. C. Schrader: A reconnaissance in northern Alaska. Professional paper no. 20, pp. 67-72.

[101] Alfred H. Brooks: Professional paper no. 45, pp. 223-225.

[102] Opus cited, pp. 60-62.

or Devonian. The Stuver formation closely resembles the Nation river, and as his determination of its stratigraphic relation to the Lisburne rests on rather incomplete evidence, there being profound faulting in this area, it is at least possible that the Stuver is younger and the equivalent of the Nation River formation. Such an interpretation would show a strong similarity between the Carboniferous section of the Yukon and the Anaktuvuk. It should be noted that Schrader reported the presence of Lower Carboniferous rocks in the Anaktuvuk basin other than the Lisburne formation. This statement was based on the evidence of fossils referred to the Carboniferous found in stream gravels and believed to be derived from some member of the Ficket series.[103] On the basis of this, the entire Ficket series, comprising some 8,000 to 10,000 feet of very heterogeneous rocks, was provisionally assigned to the Carboniferous. As no similar development of Carboniferous rocks is known in any other part of Alaska, it seems probable that they are not all Carboniferous.

At cape Lisburne, the type locality of the formation of the same name, Collier[104] found some 4,500 feet of sediments making up the Lisburne series and carrying Lower Carboniferous fossils. Three formations are recognizable in this series, as follows: A lower, made up of 500 feet of thin-bedded argillites and limestones, with several coal beds; a middle, including about 1,000 feet of clay shales, slates, cherts, and limestones; and an upper, consisting of 3,000 feet of massive limestone and cherts. Though detailed correlations can not now be made, it seems reasonable to suppose that the Lisburne is in a general way equivalent to the Calico bluff, which would indicate a thickening of the lowest member of the Carboniferous rocks to the westward.

Crystalline limestones interbedded with black phyllites occur on the eastern slope of cape Mountain at cape Prince of Wales, which were first regarded as pre-Ordovician,[105] but, on the evidence furnished by some fossil fragments found by Collier in 1903 and 1904, Doctor Girty has assigned the horizon to the Carboniferous and states that it is probably Lower Carboniferous.[106] This locality is of interest from the standpoint of dynamic history because it is the only one in Alaska where Carboniferous rocks have been recognized which have suffered any considerable metamorphism.

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[103] F. C. Schrader: A reconnaissance in northern Alaska. Professional paper no. 20, U. S. Geological Survey, pp. 70-71.

[104] Arthur J. Collier: Geology and coal resources of the Cape Lisburne region. Bulletin no. 278, U. S. Geological Survey, pp. 16-27.

[105] Alfred H. Brooks: Reconnaissance in Cape Nome and adjacent gold fields, Seward peninsula. Special publication, U. S. Geological Survey, 1901, p. 28.

[106] Arthur J. Collier, Frank L. Hess, P. S. Smith, and Alfred H. Brooks: The gold placers of parts of the Seward peninsula. Bulletin no. 328, U. S. Geological Survey, p. 81.

The Rampart region has yielded some Upper Carboniferous fossils, found in a gray and black argillaceous and siliceous slate by Prindle.[107] These rocks have been but little studied and their relation to the Devonian is not known. Lithologically they do not appear to resemble either the Nation river or the younger Carboniferous of the upper river. Spurr[108] described some limestones and carbonaceous argillites which occur on the Yukon 20 miles below the mouth of Minook creek, and on the basis of some fragmentary fossil plants assigned them to the Tahkandit.

A heavy conglomerate and argillite series in the White River region,[109] termed the Willesley formation, was provisionally assigned to the Carboniferous or Devonian on the basis of a few invertebrate fossils. It seems quite possible that this may be a synchronous deposit with the Nation River.

In the Upper Copper River basin Mendenhall[110] found a series of conglomerates, quartzites, and tuffs which he termed the Chisna formation and provisionally correlated with the Willesley. A heavy conglomerate also occurs along the western foot of the Alaska range, and this, too, may be Carboniferous.

If these conglomerates are synchronous deposits, they probably represent a far-reaching period of erosion. In the Copper-White River region it appears to be the oldest recognizable Paleozoic, resting immediately on the metamorphic rocks. If it proves to be Nation River, it indicates that the Calico Bluff, the Devonian, and possibly Silurian rocks were removed by erosion before its deposition in this region.

Upper Carboniferous terrains find an extensive development in the Copper-White River area where the Mankomen formation has been described by Mendenhall.[111] This includes 6,000 to 7,000 feet of sandstones, shales, and limestones, with much igneous material. These rocks, referred to the Permian, would here be classed as Upper Carboniferous and can be correlated provisionally with the highest Carboniferous horizon of the Yukon. The Yukon rocks include, however, only deep-sea sediments, while the rocks described carry a large amount of clastic as well as igneous material. If, then, these terrains are synchronous deposits, the

[107] L. M. Prindle: The Fairbanks and Rampart quadrangles. Bulletin no. 337, U. S. Geological Survey. (In print.)

[108] J. E. Spurr: Eighteenth Annual Report, U. S. Geological Survey, part iii, pp. 171-172.

[109] Alfred H. Brooks: A reconnaissance in the White and Tanana River basins. Twentieth Annual Report, U. S. Geological Survey, part vii, pp. 471-472.

[110] Walter C. Mendenhall: Geology of the central Copper River region, Alaska. Professional paper no. 41, U. S. Geological Survey, pp. 33-36.

[111] Walter C. Mendenhall: The geology of the central Copper River region, Alaska. Professional paper no. 41, U. S. Geological Survey, pp. 40-52.

physical conditions in these two adjacent provinces must have been very different. It should also be noted that the entire Yukon Upper Carboniferous includes only a few hundred feet of strata, while the supposed equivalent terrains in the Copper River are over 6,000 feet in thickness.

East of the area occupied by the Mankomen and in the Tanana and White River basins some limestones carrying Upper Carboniferous fossils have been found. Schrader[112] has divided these into two divisions—a lower, which he called the Suslota formation, and an upper, which he called the Nabesna formation. The latter has been traced eastward into the White River basin, where they are conformably overlaid by Triassic argillites.[113]

The Canadian geologists Keele and Camsell report a limestone between the Stewart and Peele rivers, nearly east of the Nation River localities, which, judging from the lithological description given by them, is probably the eastern extension of the upper limestone member of the Yukon Carboniferous section. This horizon is described as a "massive granular limestone containing fossils,"[114] but no collection appears to have been made. Keele refers this limestone to the Upper Paleozoic, and states that "it is a mass of white bedded crystalline limestone forming the greater portion of a mountain group."[115]

Carboniferous fossils were first reported from northern British Columbia by Dawson[116] in a siliceous crystalline limestone series which occurs on Tagish lake. Dawson correlated this limestone with the Cache Creek series, both because of lithologic similarity and because of the presence of Fusulina.[117] As in a later report Dawson[118] shows that in its typical development the Cache Creek includes 10,000 and possibly 15,000 feet of strata and may embrace some Devonian rocks, it is evident that no detailed correlation with the Yukon section can be made. Later investigators in this field have followed Dawson in correlations. Gwillim,[119] who

[112] W. C. Mendenhall and F. C. Schrader: The mineral resources of the Wrangell district. Professional paper no. 15, U. S. Geological Survey, pp. 46-47.

[113] Alfred H. Brooks: A reconnaissance from Pyramid harbor to Eagle City. Twenty-first Annual Report, U. S. Geological Survey, part ii, p. 359.

[114] Canadian Geological Survey, vol. 16, part CC, 1906, p. 16.

[115] Ibid., part C, p. 14.

[116] George M. Dawson: Report on an exploration in the Yukon district, Northwest Territory. Geological Survey of Canada, Annual Report, 1887, part B, pp. 170B-171B.

[117] In a footnote Dawson says (opus cited, p. 171B): "No critical examination of these fossils has yet been made, but they appear referable to *Fusulina robusta* (Meek), found in California."

[118] George M. Dawson: Report on the Kamaloop map sheet, British Columbia. Annual Report of the Geological Survey of Canada, new series, vol. vii, 1894, p. 46B.

[119] J. C. Gwillim: Report on the Atlin mining district, British Columbia. Annual Report of the Geological Survey of Canada, vol. xii, 1899, pp. 15B-20B.

has mapped an area lying southeast of Tagish lake, presents the following succession of Paleozoic rocks:

Greenstone, magnetite, serpentine, peridotite, and actinolite slates (in part Mesozoic).
Crystalline limestone, probably Carboniferous, cherty quartzite, black slate, biotite slate, and limestone.
Quartzite, hornblende and chloritic schists, and crystalline limestone.

Of these subdivisions he appears to regard the two middle ones as equivalents of Dawson's Cache Creek series.

In the hope of obtaining more data on the age of this limestone, Mr Kindle visited the Dawson locality on Windy arm of Tagish lake. A diligent search in the limestone yielded, however, only a few fragmentary fossils, on which Doctor Girty reported as follows:

"The only fossils obtained at this point are the following: Round crinoid stems; a small simple terebratuloid having much the shape of *Diclasma formosum* Hall, but of a type common to many horizons; a fragment of a large complanately coiled shell, not showing septa, but probably a nautiloid rather than an ammonoid; a fragment of a small chambered shell, not showing the suture line, which, as the septa are seen in the weathered section to be folded, is probably an ammonoid.

"This fauna may be Carboniferous, but the evidence is too imperfect for satisfactory determination. If Carboniferous, the facies is distinctly different from the ordinary Alaskan Carboniferous fauna, which abounds in *Productus* and other brachiopods and is almost without cephalopods. In view of this fact and the other, that the faunal relations of the Alaskan Carboniferous are much more with the Russian and Asiatic sections than with those of central United States, this fauna contains a certain suggestion of the Artinsh, but this is more of a speculation than an inference."

It is clear that these scattered facts are not sufficient, in the absence of corroboratory paleontologic evidence, for correlating this Carboniferous limestone with any of the Yukon terrains, though the writers would tentatively suggest its equivalency to the Upper Carboniferous.

In southeastern Alaska the general succession of the Carboniferous rocks is very well known. There is, however, no definite knowledge as to the total thickness of the Carboniferous, owing to the absence of any single continuous section of the entire series. At least 3,000 feet of the Paleozoic rocks are known to belong to the Carboniferous, and more complete information about the middle portion of the series may double this thickness. The lowest division of the Carboniferous comprises about 1,500 feet of dark, cherty, generally thin-bedded limestone, with a Lower Carboniferous fauna. These rocks are well exposed at Freshwater bay, on

Chichagof island.[120] The fauna of these limestones at Freshwater bay show them to be the equivalent of the Calico Bluff formation of the Yukon section. They appear to rest on an igneous series which is probably of Upper Devonian age.

The Upper Carboniferous limestone, which is about 600 feet in thickness, is exposed in the Pybus Bay section on Admiralty island. It is truncated above by a Mesozoic limestone, which is unconformable to it. A series of highly siliceous argillites of undetermined thickness underlies the Upper Carboniferous limestone at Pybus bay, of which about 800 feet are exposed. These include beds of various colored (chiefly black and red) siliceous argillites. Both the siliceous argillites and the Upper Carboniferous limestone occur on the coasts of Kupreanof and Kuiu islands, and are probably widely distributed in southeastern Alaska. The Upper Carboniferous limestone of southeastern Alaska contains a rich fauna which is so closely allied to that of the Upper Carboniferous limestone of the Yukon as to leave no question as to their equivalence. The argillite series occurring between the Upper and Lower Carboniferous limestone in southeastern Alaska should probably be correlated with the Nation River formation of the Yukon. No fossils are known from the rocks of either series, but similar relationships which they seem to sustain to the limestone formations of the two regions suggest their provisional correlation at least.

It is evident from the foregoing that, while the threefold division of the Yukon Carboniferous can not be carried through the Carboniferous section of all the adjacent provinces, yet certain of the stratigraphic units are known to have a wide distribution.

The beginning of the Carboniferous time in the inland region was marked by no period of erosion or dynamic disturbance, sedimentation being unbroken from the Devonian. There was, however, a gradual change from land-derived material to that of a purely calcareous character, which was accompanied by the appearance of a new fauna. What the limits of the sea in which these rocks were deposited were can not now be stated. It probably covered much of the present Yukon basin, and certainly covered southeastern Alaska. In northern and northwestern Alaska the oldest Carboniferous is also represented by a limestone series, but the included faunas are somewhat different from those of the Yukon. Calcareous sedimentation continued on the Yukon until probably more than 1,000 feet of strata were accumulated, and then there appears to have been elevation above the water and erosion. The suc-

[120] E. M. Kindle: Notes on the Paleozoic faunas of southeastern Alaska. Journal of Geology, vol. 15, 1907, p. 331.

ceeding strata on the Yukon are made up of littoral and in part at least of fresh-water deposits, embracing some very coarse material and aggregating nearly 3,000 feet in thickness. This same epoch of deposition is probably represented in the White-Copper River region and in the Alaskan range, where, however, it appears to form the base of the Carboniferous, indicating that, if the older limestone had ever been present in this area, it was removed by erosion before the coarse sediments were laid down. The same horizon appears to be represented in southeastern Alaska by argillites. The third epoch of deposition is one of calcareous material, and here again there was an abrupt change, this time to deep-sea conditions and marked by the appearance of a new fauna. This Upper Carboniferous sea was probably widespread. Its thickest recognized deposits are found in southeastern Alaska, but it seems quite probable that the upper limestone member of the Cache Creek series was deposited in it. Sedimentation may have continued unbroken into Triassic times in the Yukon district, but in southeastern Alaska a period of erosion intervened between the highest Paleozoic and the lowest Mesozoic.

MESOZOIC

On the evidence of the small collection of fossils alluded to above, Mesozoic deposition in this area is believed to have begun with a Triassic terrain. The fauna on which the provisional determination of the Triassic was made by Dr T. W. Stanton was found at but a single locality—between the mouth of Nation river and the extensive exposures of Upper Carboniferous limestone above the latter on the north bank of the Yukon. The fossils include a species of *Halobia* closely allied to if not identical with a characteristic Triassic form. The other species of the fauna are either new or without stratigraphic significance. This fauna occurs in a limestone exposing about 15 feet at the outcrop. The limestone apparently belongs in a shale and sandstone series immediately following the Upper Carboniferous limestone, which is but slightly exposed where the collection was made. Our very limited knowledge of this terrain makes it impossible to offer any estimate of the thickness of the beds which should be assigned to it.

The first discovery of Triassic in the Yukon basin was made by Doctor Hayes,[121] who found Triassic fossils in some slates at the head of the White river during his exploration from the Yukon to the Copper river.

[121] C. W. Hayes: An expedition through the Yukon district. The National Geological Magazine, vol. iv, 1892, p. 140.

Professor Alpheus Hyatt made the following statement regarding this find:

"The fossils in the shale are clearly the remains of a *Monotis* of a Triassic type allied to *Monotis subcircularis* Gabb—a characteristic Triassic form in California. This one seems to be distinct specifically, but is evidently of the same age."

These Triassic rocks appear to rest conformably on Upper Carboniferous limestones. A number of later investigations in this and adjacent areas have found extensive developments of Triassic rocks, consisting chiefly of argillites and limestones.[122]

Another locality of Triassic beds in the Yukon region is one reported by Keele[123] in the Stewart River basin. The fossils from these beds occur in a dark limestone associated with gray and green argillites. On the basis of these fossils Keele has provisionally assigned to the Triassic a considerable area of argillites, sandstones, grits, quartzites, and limestones. Further work will probably show that a considerable part of the area indicated as Triassic by Keele in the Stewart River region[124] is of Carboniferous or Devonian age. Whatever detailed studies may show regarding the extent of Triassic beds in this field, it is certainly important to know definitely that the Triassic sea covered portions of the Yukon basin.

The fauna obtained by Mr Keele in the Stewart River basin and referred provisionally to the Triassic by Doctor Whiteaves contains two species "having the general appearance of *Manotis subcircularis* and *Halobia lomelle*."[125]

The only member of the Mesozoic extensively developed along the Yukon are the so-called Aucella beds, which may be either Jurassic or Lower Cretaceous, but may here for convenience be assigned to the latter system. These Lower Cretaceous beds form a practically continuous belt along the Yukon from about the mouth of Fourth of July creek to Coal creek (see map, figure 2). There may be, however, some of the younger

[122] It is not proposed here to summarize the knowledge regarding the occurrence of Triassic rocks in Alaska, except in so far as it bears more or less directly on the stratigraphy of the Yukon basin. A summary statement will be found in the Geography and Geology of Alaska, Professional paper no. 45, U. S. Geological Survey, pp. 226-231. It is perhaps well to call attention to the fact here that since the summary was prepared F. H. Moffit and A. G. Maddren have found Triassic fossils in the Chitistone limestone in the Wrangell mountains, and C. W. Wright and W. W. Atwood have found Triassic fossils in southeastern Alaska.

[123] J. Keele: Report on the Upper Stewart River region, Yukon. Geological Survey of Canada, no. 943, 1906, pp. 14-15C.

[124] Ibid., map.

[125] Ibid., p. 17C.

Tertiary beds included within this area which were overlooked in the hasty examination.

The Lower Cretaceous of the upper Yukon comprises a series of closely folded rocks characterized by a large amount of silica. They included primarily siliceous slates, slaty sandstones, and quartzites, with which are associated some argillites and pyroclastics. One heavy bed (50-70 feet thick) of massive tufaceous conglomerate was observed within the Mesozoic area about 5 miles below Washington creek, but may be an infolded older or younger terrain. The pebbles of this conglomerate, which are chiefly limestone, are well rounded, and some are 2 feet in diameter. The dominating rock type of the Lower Cretaceous is a siliceous slate or quartzite, sometimes interbedded with a clay slate. These rocks are usually pyritiferous and iron-stained when weathered. Three miles below Washington creek there is a series of beautifully banded slates and quartzites. Here the brittle quartzite is broken by a series of fractures at right angles to bedding, while the same movement has in large measure been taken up in the cleavage of the slate. A quartz filling, sometimes carrying pyrite, is not uncommon along these fractures. In at least one instance it appears to be established that quartz veins cutting these Cretaceous rocks are auriferous. This conclusion is not without importance in its bearing on the age of the mineralization which produced the auriferous deposits of the Yukon.

These rocks in a general way strike easterly and northeasterly, but there are many local variations. They are usually closely folded, and no determination of thickness, which probably does not exceed a few thousand feet, could be made. On Washington creek they appear to rest unconformably on the Devonian and in turn are unconformably overlaid by the Tertiary beds. Near Coal creek the Aucella-bearing beds seem to underlie the Upper Carboniferous limestone, which has apparently been thrust over them.

Fossils were collected from three localities in this formation, which were reported upon by Dr T. W. Stanton as follows:

Lot 18.—South bank of the Yukon river, 400 yards below Glen creek:

This lot includes many fragmentary specimens and impressions of an Inoceramus, with a few imperfect specimens of Pecten, Pinna, two small specimens doubtfully referred to Aucella, and a few other small undetermined bivalve shells, together with very imperfect fragments of an ammonite possibly belonging to the genus *Perisphinctes*, or some other genus with a similar sculpture. The horizon of this lot is evidently either Jurassic or Lower Cretaceous, but the nature of the material does not permit a discrimination between these two periods. I judge that these fossils came from the same series as the Aucella mentioned below.

Lot 19.—North bank of Yukon river, 6 miles above Charlie village:

This collection contains numerous specimens of Aucella cf. *crassicollis* Keyserling. This is provisionally referred to the Lower Cretaceous, although the possibility that it may be Jurassic should not be forgotten.

Lot 21.—South bank of the Yukon river, 1½ miles below Sams creek:

This small lot contains two imperfect specimens of Aucella and a few small fragmentary imprints of Inoceramus. The horizon is probably the same as that of lot 19.

The reference of these three lots of fossils provisionally to the Lower Cretaceous is made with the same reservation that has so often been expressed when similar collections containing Aucella and only a few associated forms have been submitted from this and other areas in Alaska—that is, while the Aucella itself is indicative of probable Cretaceous age, closely related species are known in the Jurassic, and it may be that all of the Aucella beds of Alaska are Jurassic.

These Aucella-bearing beds of the upper Yukon were included by Spurr[126] in his Mission Creek series, which he provisionally assigned to the Upper Cretaceous or Jurassic. As, however, he also included in his Mission Creek terrains which have since proved to be either Tertiary or Paleozoic, it does not appear to be advisable to perpetuate this name as a stratigraphic unit. The same rocks have also been described by Collier,[127] but he did not propose any formation name, nor does it seem desirable to do so here, in view of the paucity of the information regarding these beds. Sediments of the same age are widespread in Alaska, but will not be discussed here.

In 1905 Prindle[128] and Hess reported the occurrence of a Cretaceous sandstone in the Rampart region. More recently Prindle[129] has revisited this locality and found fossils assigned by Doctor Stanton to the Upper Cretaceous. The rock in which this fauna occurs is a black, carbonaceous, sandy argillite. Granitic rocks are found cutting these beds, showing a later intrusion of acid rocks than was previously known. Collier[130] found Upper Cretaceous beds on the lower Yukon near Nulato, but aside from these this horizon is unknown in central Alaska.

TERTIARY

The most widely distributed formation of the Yukon basin is repre-

[126] Opus cited, pp. 175-184.

[127] Arthur J. Collier: The coal resources of the Yukon. Bulletin no. 218, U. S. Geological Survey, pp. 16-17.

[128] L. M. Prindle and F. L. Hess: The gold placers of the Rampart region. Bulletin no. 280, U. S. Geological Survey, p. 22.

[129] L. M. Prindle: Descriptions of the Fairbanks and Rampart quadrangles. Bulletin no. 337, U. S. Geological Survey. (In print.)

[130] Bulletin no. 218, U. S. Geological Survey, pp. 15-17.

sented by a series of conglomerates, argillites, and sandstone usually carrying more or less lignite. This formation, first described by Spurr, has been correlated with the coal-bearing rocks of the Kenai peninsula, called the Kenai formation. The correlation is based both on the lithologic similarity and stratigraphic sequence and on the evidence of paleobotany. As this paper treats chiefly of the Paleozoic rocks, the various problems connected with the distribution of the Kenai formation will not be here discussed. It has been shown by Collier[131] and confirmed by Arthur Hollick that the Kenai of the lower Yukon includes not only Tertiary, but also some Cretaceous beds—that is, it represents an unbroken sequence from the Upper Cretaceous through to the Tertiary. While a similar sequence has not yet been established on the upper river, it is by no means impossible that such may exist. Dr F. H. Knowlton, who is the authority on the Kenai plant remains, assigns them to the Upper Eocene or Arctic Miocene, as it sometimes has been called, with the reservation, however, that in some cases they may include some Upper Cretaceous beds.

The Kenai of the upper Yukon embraces rocks of rather divergent character. In some instances the rocks are well indurated, being made up of hard conglomerate, sandstones, and sandy and clayey shales or slates, while in others the sandstones are almost unconsolidated and the argillites very little indurated. This local divergence in lithologic character sometimes makes the identification of the Kenai formation difficult when paleontologic evidence is lacking. The friable phase of this formation is easily differentiated from the other conglomerate-bearing terrains, but the indurated conglomerates, sandstones, and shales are often very similar to the rocks here called the Nation River formation. It is quite possible, therefore, that on the accompanying map some Kenai beds may be included with the Nation River, and, on the other hand, that some of the beds mapped as Kenai may in part belong to the Carboniferous. Mr Prindle, who has studied the Tertiary of the Seventymile basin, states that the indurated phase of the Kenai and the friable phase are there found close together.

The thickness of the Kenai formation was not determined by our observations. It probably varies much locally, and in some instances may attain a thickness of several thousand feet. In others it may be measured in hundreds of feet.

The Kenai formation has usually been described as occurring in local

[131] Arthur J. Collier: The coal resources of the Yukon. Bulletin no. 218, U. S. Geological Survey, p. 17.

basins, either of lacustrine or fluviatile origin. That described here appears, in part at least, to be of fluviatile origin. The distribution, as represented on the map (figure 2, page 278), indicates that a belt of the Kenai rocks runs parallel to the Yukon from Eagle to Birch creek. While this zone has not been traced continuously, it is sufficiently well known to justify the opinion that it was originally deposited as one continuous belt. The outline of this formation, as represented on the map, is in part based on the observation of Prindle and on statements made by prospectors. The distribution, as will be seen, is very suggestive of an old river channel, and the lithologic character rather bears out this assumption. Moreover, the conglomerate of the Kenai on Woodchopper creek and Seventymile have been found to be auriferous, which also lends weight to the assumption that the deposits are of fluviatile origin.

No beds have been identified on the Yukon which are positively known to belong to the Pliocene or Miocene. It seems probable, however, that some terrace deposits may be of late Tertiary age. Such interpretation of the facts in hand has been made by both Spurr[132] and Collier.[133] These beds were not studied by the writers, and will therefore not be described here.

QUATERNARY

The deposits included in the Quaternary embrace two groups: (1) the sand, gravels, and silts of the present drainage system, and (2) the gravel, sands, and silts occurring as terraces along the Yukon and its tributaries, which, in the absence of evidence to the contrary, can be assigned to the Pleistocene. The scale of the map and the lack of detailed information have made it necessary to indicate both groups of deposits simply as Quaternary.

The recent deposits need no detailed description. Along the Yukon they include coarse gravel, found both in the river bars and in low terraces, while in the smaller tributary streams they constitute the flooring of the valleys. Near Circle, where the flat of the Yukon begins (see map, page 278), the stream deposits are chiefly fine silt, often frozen, and at low and medium waters standing as a bluff 10 to 20 feet above the river level. The gravels of the smaller streams are usually coarse, containing very little silt.

The deposits here grouped as Pleistocene embrace some stream terraces and extend from 25 to 200 feet above the present waterlevel. Specially

[132] Geology of the Yukon gold district, pp. 196-200.

[133] The coal resources of the Yukon. Bulletin no. 218, pp. 16-18.

noteworthy are some high gravel deposits which lie on a well defined rock bench some 200 feet above the river at Calico bluff. The section of this deposit showed about 10 feet of coarse river gravel resting on bedrock, succeeded by 20 feet of fine silt. The base is about 160 feet above the river. The rock bench on which this deposit rests, traceable from Dawson down the Yukon to Calico bluff and beyond, appears to mark an old valley floor. The same epoch of erosion has been noted in some of the tributary streams, such as Fortymile, where old valley floors are found above the present waterlevel and probably mark the same cycle of erosion as that of the high gravels (White channel) of the Klondike.

At the mouth of several of the northern tributaries of the Yukon heavy deposits of silts are found resting on a rock bench about 200 feet above the river. The fact that these silts occur only along the streams whose sources lay in a glaciated region suggests that they are probably of glacial origin. In other words, they represent the overwash deposits of a retreating ice-sheet which, however, did not reach the Yukon. At the mouth of Sheep creek these deposits are found to have a thickness of 500 to 1,000 feet. They are essentially buff-colored fine silt, with some clay beds, showing very little evidence of stratification, but usually rest on a stratum of gravel or sand. Spurr[134] has described these elevated alluvial deposits at some length under the name "Yukon silts," and has suggested a glacial origin for at least those of the upper river. When these deposits, which are found for 2,000 miles along the Yukon and Lewes rivers, are mapped in detail, it will undoubtedly be found that they include material of quite diverse origin. The occurrence in them at many localities of vertebrate remains adds interest to the problem of the genesis of these deposits. Maddren[135] has recently summarized the available data bearing on their distribution and origin.

STRUCTURE

In the foregoing pages an account of the structure of each individual stratigraphic unit has been presented, so far as the facts are available. It is proposed to here summarize this data and to point out the larger structures of the province.

The general trend of the dominant structure lines has already been referred to and emphasis has been laid on their crescentic swing through the province here under discussion. Thus, in the Rampart region and

[134] Geology of the Yukon gold district, pp. 200-221.

[135] A. G. Maddren: Smithsonian exploration in Alaska in search of mammoth and other fossil remains. Smithsonian Miscellaneous Collections, vol. xlix, 1905, pp. 1-117.

near the mouth of the Tanana, the prevailing strikes are north 60 to 70 degrees east. Passing eastward, the structures gradually swing, until at the 146th meridian they are about east and west, and from here to the International boundary they gradually swing to the southeast. Not only do the prevailing strike lines of the bedding planes conform to this general system, but the major joint planes also mark a crescent opening toward the south. The dips are varied, but the majority are steep and northerly.

The structures above described are those of the Mesozoic and older rocks. Folding since Eocene Tertiary times has been rather local and not very intense, and the structures of terrains of that period of deposition do not always conform to the above system. There is, however, a general parallelism between the belt of Tertiary which stretches westward from the International boundary and the structures of the older rocks. This may be explained by the fact that these rocks represent the deposits of a Tertiary river whose drainage lines were determined by the bedrock structures of the older terrains.

The general distribution of the terrains (see map, page 265) indicates that pre-Ordovician metamorphic sediments are exposed along a broad truncated anticlinal uplift or anticlinorium. Such an interpretation was first suggested by Spurr, on the basis of his studies made in 1896. Within this broad uplift there are an infinite number of smaller folds, for the deformation has been exceedingly intense. In fact, so crumpled are the old metamorphic schists that it appears hopeless to determine their detailed structures. The Devonian and Carboniferous rocks are far less disturbed than the older sediments. This may be in part because they were not so near the axis of maximum movement, but is due largely to the fact that they were deposited after the earlier crustal movements which affected the Ordovician rocks. Northeast of the Yukon valley two anticlinal uplifts cross the Porcupine river, exposing rocks older than any of those traversed by the Yukon below the International boundary. These rocks along the Porcupine are but little altered, as compared with the older terrains to the southwest of the Yukon.

OUTLINE OF GEOLOGIC HISTORY

It is intended here to present in brief review the succession of geologic events which have affected the province under discussion. It will be evident from the foregoing that the fragmentary nature of the data does not permit of a close definition or analysis of the various epochs of deposition and earth movements which have produced the terrains here dis-

cussed, but attention will be directed to some of the salient features of the geologic history.

It has been shown that the oldest rocks are included in a complex series of metamorphic sediments and intrusives. Among these sediments fine-grained clastic material dominates, suggesting deposition at some distance from land. To what geologic age the sea in which these sediments were deposited belongs is not known.

Reasons have been advanced in the foregoing pages for believing that these metamorphic rocks belong to the pre-Ordovician. In view of the great thickness of Cambrian strata (40,000 feet) reported by Dawson[136] in the adjacent province of British Columbia, it seems fair to assume that these sediments may, in part at least, be of Cambrian age. In still greater doubt is the age of the metamorphism which converted these sediments into schists and crystalline limestones. There were undoubtedly several periods of crustal movements during early or pre-Paleozoic times; the latest producing any considerable amount of metamorphism probably took place in late Silurian or early Devonian time. The evidence of this lies in the probable Silurian age of the intrusive gneissoid granites which were involved in this folding and also in the fact that there appears to be a sharp line of demarcation between the Middle Devonian and pre-Middle Devonian rocks. The semicrystalline character of the oldest metamorphic rocks may be due, as suggested above, to their having suffered alteration previous to the deposition of the known Paleozoics, but also may be largely due to their having been more deeply buried or lying closer to the axis of maximum disturbance.

If any conclusions are warranted, on the fragmentary evidence at hand, as to the extension of the Ordovician sea, it will be that it covered northern British Columbia, much of the Yukon and Kuskokwim basins, and the Seward peninsula. Indeed, everywhere that Ordovician sediments have been found the usual absence of detrital material would indicate a much wider extent of the sea. As the Ordovician fauna of Alaska is European and Asiatic rather than North American, a barrier is to be expected between this sea and the other Ordovician seas of North America.

There is no evidence of a crustal movement intervening between the Ordovician and Silurian of Alaska. If, however, the fragmental rocks of the Rampart region prove to be Silurian, as believed, there must have been a very decided change in the physical conditions, suggesting a crustal disturbance of some magnitude. It has been shown that the Silurian

[136] George M. Dawson: Geological record of the Rocky Mountain region in Canada. Bulletin of the Geological Society of America, vol. 12, 1901, p. 62.

sea was of wide extent, but the fragmental rocks of the Rampart region indicate that there was a landmass not far away. It is probable, though not proven, that the intrusion of the granites now preserved in part as augen-gneisses took place in Silurian or early Devonian times. The conditions during the earliest Devonian time, like those of the preceding periods, are very much in doubt. The heavy limestone and associated rocks of the Upper Yukon section, here assigned to the early Devonian, indicate deep-sea conditions; but, again, these may be of Silurian age. It seems probable that one of the recurrent epochs of crustal disturbances took place in early Devonian or late Silurian times, for all the rocks laid down before this period appear to fall in the metamorphic class, though they have suffered a varying degree of alteration. It is probable that this epoch was closed by an uplift followed by erosion.

In the Yukon section proper the oldest definite stratigraphic tie-point is a white crystalline limestone carrying a Middle Devonian fauna, and this horizon appears to be widespread in Alaska, indicating that much of the province was submerged during this period. On the Yukon this was accompanied and probably succeeded by extensive extravasation of igneous rocks. Volcanism continued until thousands of feet of material had accumulated. There is some evidence that this period of igneous activity, though intense, was very local, and that during it normal sedimentation was going on in near-by localities.

In any event, deposition continued unbroken from the latter part of the Devonian into the Carboniferous, the only change being a gradual lessening of land-derived material and the appearance of a new fauna. Deep-sea sedimentation continued for a long period, and in a sea which probably covered most of Alaska. A second cycle was inaugurated by an uplift accompanied by extensive erosion and the deposition of coarse clastic material, in part, probably, laid down in fresh water. The period of erosion was long enough in some parts of the province to remove all the strata down as far as the metamorphic terrains.

The close of the Carboniferous was marked by a widespread invasion of a sea which probably covered all Alaska and much of the adjacent provinces. In the Copper River region late Carboniferous sedimentation was accompanied by another volcanic outburst. There is some evidence to suggest that in the Yukon basin there was no break in sedimentation between the Carboniferous and the Triassic. Jurassic rocks are unknown on the Yukon, and as the Lower Cretaceous rests unconformably on the older terrains, it is probable that they were preceded by a cycle of erosion. The folding of the Lower Cretaceous beds marked the close of extensive

crustal disturbances. Though the Tertiary beds are folded and there have been many orographic movements in this province since Lower Cretaceous times, they belong to a different order of magnitude. These crustal disturbances have done little to obscure the effects of the older crustal movements, which have determined the dominating structural features of the region. It is worthy of note that some of these later crustal movements were accompanied by granitic intrusions which have cut Upper Cretaceous beds. A discussion of the complex recent orographic history of the region, with which is involved the genesis of the land forms, is no part of the purpose of this paper.

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GEOLOGIC RECONNAISSANCE OF THE PORCUPINE VALLEY, ALASKA[a]

BY E. M. KINDLE

(Presented by title before the Society December 31, 1907)

CONTENTS

Topography and Drainage

Topographically the country traversed by the Porcupine river between the International boundary and the Yukon falls into two distinct provinces. The most easterly of these includes the low mountain and hill country extending westward from the boundary about 100 miles. The Yukon flats comprise the westerly belt.

A little more than 100 miles of the lower course of Porcupine river lie in the extensive alluvial plain known as the Yukon flats. Along this

[a] Manuscript received by the Secretary of the Society July 4, 1908.

portion of the river hard rocks nowhere outcrop. The banks rise generally 12 to 18 feet above low water and never more than a few feet above high water. Entirely without topographic relief, this extensive region is covered with muskeag, spruce forest, and willows. The latter occupy the intermediate border between the swampy muskeag and the better drained spruce forest tracts, as well as the areas subject to river overflow. Numerous sloughs or side channels diverge from the river, often keeping independent courses for many miles before they rejoin the main stream. These increase in number and complexity toward the mouth of the stream, where it splits up into a number of separate channels, which join the Yukon along the western margin of a maze of islands. Three streams of considerable volume join the Porcupine in this flat. These are the Big and Little Black rivers, from the southeast, and the Salmon river, from the north. Each of these streams, like the Porcupine, has its source in a mountain region, but traverses a wide tract of the Yukon flats before joining the Porcupine. Prospectors report that the first hills and bedrock are encountered on the Salmon river "60 or 80 miles" from the Porcupine. Notwithstanding the extreme flatness of the plain traversed by the Porcupine, it has a very decided tilt toward the west, as shown by the strong current, averaging 4 or 5 miles an hour.

The elevated area lying to the east of the Yukon flats includes two distinct mountain belts, both trending north and south. The more westerly of these mountain belts lies immediately east of the Yukon flats and comprises a range of low mountains and hills. These have gentle slopes and are sparsely wooded nearly to their summits. Their maximum elevation probably does not exceed 3,000 feet. They approach the river as low hills. This western hill and mountain belt appears to be coextensive in width with the Lower Ramparts, a term used to designate the low, nearly continuous limestone cliffs which form the channel of the river for about 25 miles above the Yukon flats. A few outlying hills break up the eastern edge of the Yukon flats, but they are distinctly lower than the main range of the Lower Rampart hills. This is doubtless due in part to the fact that the former are composed mainly of shales and the latter of limestone.

The second mountain belt lies near the International boundary. It appears to show somewhat stronger relief than the belt just described, but the maximum elevation attained near the river probably does not exceed 3,500 feet. The highest point seen within 6 or 7 miles of the river on the north rises 1,640 feet above the Porcupine. This eastern mountain and hill belt appears to be confined to a zone of rocks in which quartzites predominate. These quartzites doubtless in part determine its position.

Between the eastern and western mountain belts described a topographically distinguishable zone intervenes. This is the low, nearly level basin between the Upper and Lower Ramparts. This basin is floored by Tertiary beds and Recent silts. It is drained on the north side of the Porcupine by the Coleen river, from which it has been named the Coleen basin by Maddren.[1] The north and south extent of this basin is unknown, but it is probably considerable. Its east and west extent, as measured along the river, is about 25 miles. This old Tertiary basin terminates abruptly on the east at the foot of the Upper Ramparts, where walls of Paleozoic rocks 200 to 300 feet high confine the river to a narrow gorge. On the west it extends a short distance beyond the Coleen river.

Structure

Folds

It is not the intention to attempt here a complete interpretation of the structural features involved. They include both folding and faulting and are expressed by a perplexing amount of variation in strikes and dips which have been interpreted only in part and in reference to some of the more conspicuous structural features.

The Paleozoic rocks of this region everywhere show the effects of extensive deformation. The strike of the beds, although highly variable, has a general northerly and southerly trend. The very evident northerly and southerly trend of some of the more conspicuous topographic features, resulting in part from deformational agencies, confirms the opinion that the northerly and southerly direction of the strike extends well beyond the river along which all of the direct observations on the structure were made. Deformation of the rocks seems to have expressed itself in two classes of folds, which may be distinguished as large and small, since they differ very considerably in magnitude. The latter are sometimes partially overturned, and where this has been observed the overturn is always toward the east, thus indicating that the pressure came from the west. Examples of partially overturned folds occur at the lowest outcrops on the river and at a point 2½ miles above the mouth of Coleen river. The older rocks are in part concealed over a considerable area by Tertiary and Recent silts above the Coleen river, and by lavas in the Upper Ramparts, but the exposures observed suggest that the small type of folding predominates in the belt extending from the Coleen to Camp-

[1] A. G. Maddren: Smithsonian exploration in Alaska in 1904 in search of mammoth and other fossil remains. Smithsonian Miscellaneous Collections, vol. xlix, 1905, p. 12.

bell river. Folds ranging from a few hundred yards to perhaps a mile in width occur in this region.

Two anticlinal uplifts of the larger type occur in the region. One of these is coextensive in width with the Lower Ramparts; the other includes the beds exposed for about 7 or 8 miles below the International boundary. A large number of observations in dip and strike were made near New Rampart House, just above the boundary. In 90 per cent of these the strikes ranged between north 25 degrees west and north 45 degrees west. In every case the dips observed were westerly. Westerly dips continue down the river for 7 miles, ranging from 20 to 60 degrees, but averaging perhaps 35 degrees. The northwesterly strike prevailing at the boundary sometimes swings to northeasterly. These westerly dips appear to belong to the western limb of an anticline having its axis east of the boundary a short distance. The reconnaissance was not continued far enough beyond the boundary to ascertain its position. The beds elevated to the surface by this uplift include a large proportion of quartzites. These offer greater resistance to weathering than the surface Paleozoic beds to the westward, which are largely shales and limestones. The north and south mountain belt near the boundary is consequently the result of the anticlinal structure just described, which has brought the quartzites within reach of the sculpturing agencies of erosion.

The second anticlinal uplift of the larger type includes the limestones exposed in the Lower Ramparts. A belt of Silurian and Ordovician limestones 14 miles in width trends north and south across the Porcupine at the Lower Ramparts. They are flanked on both sides by rocks of younger age. The normal dips which should characterize broad, simple anticlinal folds have been complicated by faults, two of which have been recognized, while there are doubtless others which have not been recognized.

Applying the name of the shallow gorge through which the river crosses this fold, it may be called the Lower Rampart anticline. This fold finds topographic expression in a series of low ranges of mountains and hills trending north and south.

FAULTS

The most extensive fault which has been recognized crosses the river immediately below the western entrance to the Lower Ramparts. The plane of this fault has not been seen, but it has been recognized through the discordance in the succession of the faunas and its position is known within about 100 yards.

On the north bank of the river, at the entrance to the Lower Ramparts,

bluish gray Ordovician limestone outcrops. Not more than 250 yards below it, on the same side of the river, Carboniferous shales outcrop. These continue to outcrop for 2 miles farther down the river, dipping to the westward. Carboniferous and Ordovician beds thus occur in adjacent outcrops, the entire Devonian and Silurian series being faulted down out of sight. The fault is parallel with the trend of the Lower Rampart fold and apparently cuts its western limb. The amount of throw is represented by the total thickness of the Devonian and Silurian. This can hardly be less than 4,000 feet and may be much more. The effect of a fault of this magnitude which parallels the principal axis of folding in the region on the areal distribution of the rocks is considerable. To the westward of it the rocks are all of Carboniferous age, while to the eastward lie the Silurian and Ordovician limestones. In the Carboniferous rocks lying to the westward of the fault shales predominate, while magnesian limestones comprise the bulk of the formation immediately to the east. The marked differences which these two kinds of rock exhibit in their powers of resistance to the agencies of erosion are very distinctly represented in the two distinct types of topography seen on the two sides of the fault. To the east rises abruptly the belt of hills and low mountains standing from 400 to 2,000 feet above the Porcupine. On the west lie the Yukon flats, showing no topographic relief except for a few low hills generally not more than a hundred feet high near the eastern margin.

A few rods to the eastward of the fault just described a small fault occurs on the north side of the river. The throw of this fault is very small, rocks of the same formation appearing on both sides of it. It seems quite possible that a fault may determine the eastern limit of the Coleen basin. This basin is terminated abruptly on the east by a steep ridge 500 feet high at the entrance to the Upper Ramparts. The sharp topographic contrast between the flat plain of the Coleen basin and the precipitous high north and south ridge which bounds it on the east is very suggestive of a faultscarp. There is, however, no supplementary evidence of the suggested fault available.

In the Upper Ramparts, below Salmontrout river, the Porcupine crosses a fault block 4 or 5 miles in width. Both physical and faunal evidence indicates that a fault block has been dropped down here. The outcrops below the Indian village half a mile show the limestones to be much broken up for 30 or 40 yards. Evidence of faulting is also seen on the south side of the river 4 miles lower down. According to Mr Girty's determinations, the Carboniferous limestones adjacent to the Devonian beds are of Upper Carboniferous age, indicating that the Lower

Carboniferous series has been faulted out of sight. The downthrow would seem to be 1,000 feet or more.

It might be assumed on *à priori* grounds that in a region where folding such as has been described prevails, faults, if present, would be of the thrust type. Those which are known, however, are all normal faults. Had faulting occurred at the time of folding, the resulting faults would undoubtedly have been thrust faults. The normal faults which are present we must conclude, then, were developed either before or subsequent to the folding. Their origin is believed to have been of subsequent date.

Stratigraphy and Faunas

PRE-ORDOVICIAN SERIES

The oldest rocks exposed in the Porcupine River section are found in the vicinity of the International boundary. The distribution of these older beds and the later terrains is shown on the map, figure 1. This series is well exposed in the steep slopes and cliffs facing the river at New Rampart House and outcropping continuously for 6 or 7 miles below there. It is composed largely of thin-bedded and very fine-grained quartzites, which are bedded usually in thin strata 1 to 6 inches thick. Intercalated with the quartzites are considerable beds of black shale and limestone and thin beds of dolomites. The nearly universal color of the quartzites is light gray or white, which gives them a strong resemblance to limestones. Occasional beds occur, however, which are specked with brown, and one 30-foot bed of dark-brown sandstone was observed in the river bank at New Rampart. Sulphide of iron is present in some of the beds, as is indicated by the accumulation of films of sulphur on protected rock faces. Where exposed to weathering the quartzite beds disintegrate to a fine white or cream-colored impalpable powder. This powder covers all the steep slopes where vegetation is absent, giving the appearance of great marl or clay beds at a little distance.

The black shales and slates occur usually as thin carbonaceous films alternating with limestone bands one-half inch to 3 inches thick. The presence of the limestone, although it comprises the bulk of these beds, is not evident in the weathered exposures of steep slopes, where the intensely black shale or slate fragments are apt to conceal the light-colored, thin limestone strata, giving the whole the appearance of a shale or slate formation. Below New Rampart House 1 mile a set of these black beds 500 or 600 feet thick is intercalated in the quartzite series. The latter series is well exposed in the gorge of the small stream entering the Por-

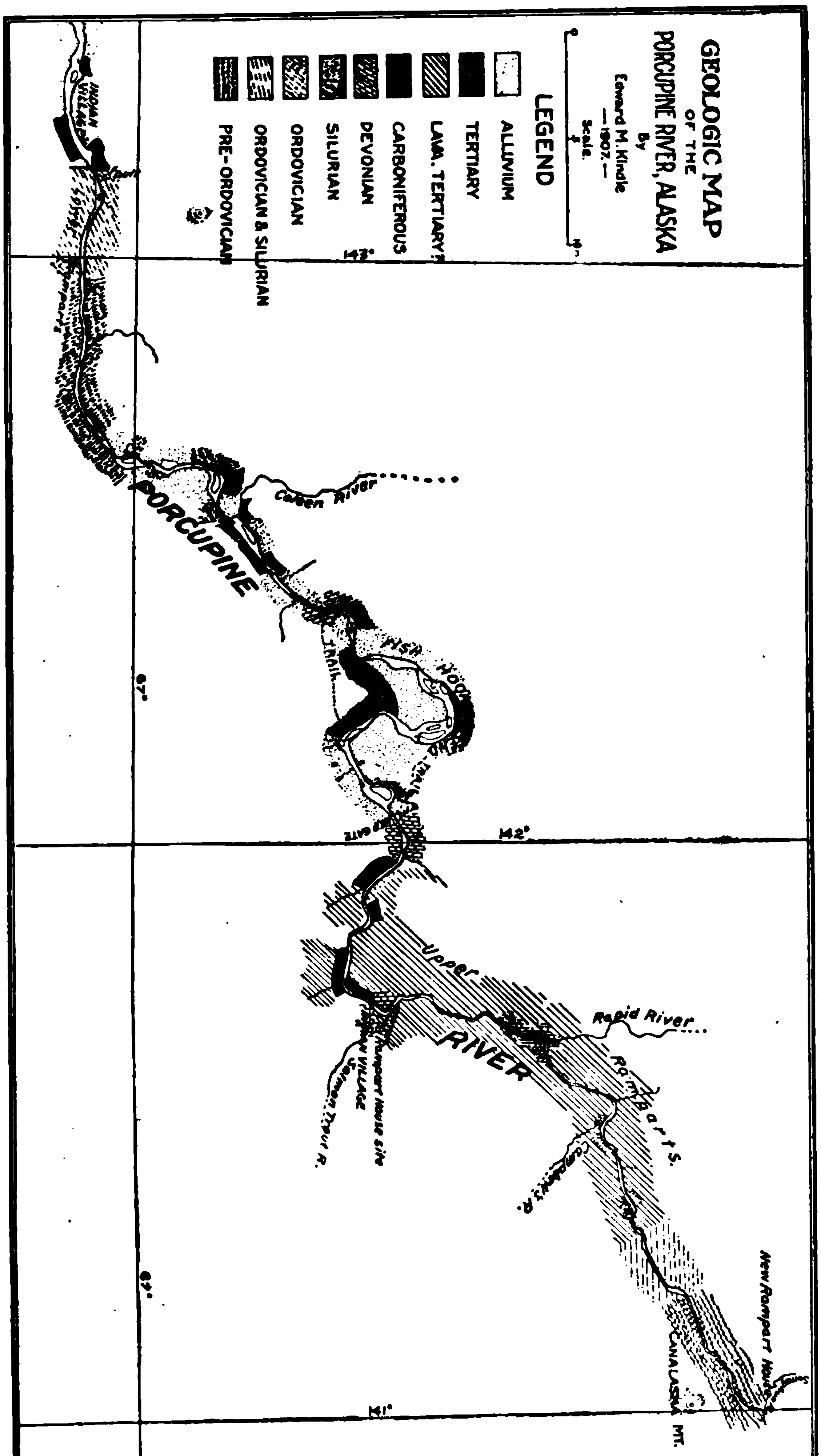

FIGURE 1.—*Geologic Map of the Porcupine River, Alaska*

cupine at New Rampart House. The creek section exposes here 1,000 feet or more of the quartzite series, which is uninterrupted by other beds. The sharp contrast of the exposures of the intensely black slate-limestone beds and the white quartzites is one of the most striking scenic features of the Upper Rampart gorge near the boundary. Some dolomites also occur in the quartzites, but they play a subordinate rôle as regards their importance in making up the total mass of the series.

Metamorphism is not very pronounced in this series, but the argillaceous sediments are noticeably more altered than those of the higher horizons. In the latter the shaly phase is found, as a rule, while in the former the shales have been altered to slates or slaty-like slickensided films where they are in very thin sheets interleaved with limestones, as generally happens.

It is difficult to make any estimate of the thickness of these beds without detailed work. The prevailing westerly dip, which continues for about 6 miles below New Rampart House, points to a great thickness for the series, but the possibility of faulting and of close folding in a part of the series leaves some uncertainty in regard to the actual thickness. Five thousand feet would seem to be a conservative estimate, and it is probable that a much greater thickness is represented.

No fossils have been found in these rocks; consequently their age can only be stated with reference to that of the oldest paleontologically determined beds of the section—the Ordovician. That they antedate the Ordovician in age is indicated by the fact that no series corresponding to them in lithologic features occurs in the portion of the geologic section lying above the Ordovician. The several main divisions of the Paleozoic section from the Ordovician to the Carboniferous have been recognized on the Porcupine by their fossils.

ORDOVICIAN LIMESTONE

The Ordovician limestone is the earliest horizon which has been recognized by fossils. On the geologic map it has been practicable to distinguish the Ordovician and Silurian in only a portion of the area of their occurrence. The Ordovician as well as the Silurian probably occurs in the Upper Ramparts between the mouth of Rapid river and the western border of the series just described. No fossils have been found, however, in any of the horizons exposed along this portion of the river. Ordovician rocks have been positively identified only in the Lower Ramparts, where characteristic faunas were found at two localities. One of these is at the lower entrance to the gorge. The second locality is some 3 miles above the first. The Ordovician limestone is a hard bluish gray rock,

with occasional oolitic bands. The beds are much checked up by joints and frequently the bedding is not recognizable. At one point the beds are much contorted and stand nearly vertical. The thickness of these beds may be roughly estimated at not far from 600 feet. Their stratigraphic relations to the Silurian beds were not determined.

The character of the Ordovician fauna is shown by two lots of fossils from localities in the Lower Ramparts.

ORDOVICIAN FAUNA

An Ordovician fauna was found at two localities in the bluish gray limestones of the Lower Ramparts of the Porcupine. One of these is on the north bank of the river, 1½ miles above the Indian village, at the lower end of the Ramparts. This fauna, although meager in the number of both species and individuals, clearly indicates an Ordovician horizon. Mr E. O. Ulrich recognizes the following species in the fauna:

Lichenaria sp. undet.
Streptelasma (*Petraia*) cf. *profundum* Conrad.
Hormotoma near *trentonensis* U. & S.
Trochonema cf. *umbilicatum* Hall.
Maclurea cf. *nitida* U. & S.
Cameroceras sp. undet.
Gomphoceras sp.
Illænus sp.
Bumastus cf. *trentonensis* Emmons.

Mr Ulrich considers this fauna to represent a Mohawkian or Middle Ordovician horizon.

Higher up the Porcupine, on the south side, about 6 miles above the Indian village and three-fourths of a mile below some high cliffs on the north side of the river, is a second occurrence of Ordovician fossils. The following fauna was secured:

Clitambonites sp.
Porambonites intercedens Pander ?
Lycophoria ? sp.
Maclurina manitobensis Whitf.
Maclurina subrotunda Whitf.
Asaphus ? sp.

The second fauna, like the first, occurs in a bluish gray limestone. Some of the beds show an oolitic structure. In some places the original bedding of the limestone is obliterated by innumerable joints. At one point these beds stand vertical in the upper part of the cliff, and are variously contorted near the base. The Ordovician limestones seem to be generally distinguishable from the Silurian by their gray or bluish gray color and more magnesian character, the latter having generally a buff color and a high percentage of magnesia. The complication of the structure and the close interrelationship of the beds of the two horizons wrought by folding and faulting make a close estimate of the thickness

of either impossible. The thickness of the older series exposed, however, is probably not far from 600 feet.

In the Yukon section the Ordovician does not appear, the oldest beds being of late Silurian age. If we may judge from the widely scattered localities from which it has been reported, the Ordovician fauna had a wide distribution in the northern part of the continent.

Collier's collections from the Seward peninsula indicate the presence in the western part of Alaska of a fauna similar to that found on the Porcupine. *Maclurina manitobensis* is one of the species recorded by Collier.[2]

In the Mount McKinley region Brooks has secured fossils of Ordovician age.[3] Ordovician faunas are therefore known from the three widely separated regions of northeastern, south-central, and western Alaska.

In the Arctic and sub-Arctic lands of northeastern America Ordovician strata have been shown by the collections secured by Schuchert,[4] Schei,[5] Low,[6] and others to have a rather wide distribution. Of these the collection from Baffin Land studied by Schuchert is the only one which is complete enough to give an adequate idea of the Ordovician of the northeastern portion of the continent.

SILURIAN DOLOMITES

The low, nearly continuous cliffs which border the Porcupine river for about 20 miles just above the northeastern margin of the Yukon flats are called the Lower Ramparts. A Tertiary basin which the Porcupine crosses separates these lower cliff walls of the river from another and much higher series of canyon-like walls known as the Upper Ramparts, which extend from the boundary, with some interruption, down to the Coleen basin.

Buff-colored magnesian limestones comprise the greater part of the rocks of the Lower Ramparts. Only a rough estimate of the thickness of these limestones can be made. Probably 2,500 feet of these dolomites are exposed in the Lower Ramparts. Some black shaly beds are associated with them, but comprise only a small proportion of the series. Occasional drab magnesian shales occur and rarely a thin bed of quartzite.

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[2] Professional paper no. 2, U. S. Geological Survey, 1902, p. 21.

[3] Bulletin of the U. S. Geological Survey, 1904. (In preparation.)

[4] On the Lower Silurian (Trenton) fauna of Baffin Land. Proceedings of the U. S. National Museum, vol. 22, 1900, pp. 143-177, pls. 12-14.

[5] New Land: Four years in the Arctic regions, by Captain Otto Sverdrup, with geological appendix to vol. 2 by P. Schei, 1904, pp. 457-458.

[6] The cruise of the *Neptune*. Report on the Dominion government expedition to Hudson bay and the Arctic islands, by A. P. Low, Ottawa, 1906, pp. 322-336.

Locally considerable masses of the limestone have been altered to calcite. While strike and dip can generally be made out and appear to conform to anticlinal structure, occasionally the bedding is entirely obliterated.

MIDDLE SILURIAN FAUNA

The magnesian limestones of the Lower Ramparts on the Porcupine river are characterized by a Middle Silurian fauna closely related to the Niagara fauna of the central United States, as well as to the cosmopolitan fauna (Silurian) of Europe and Asia. The character of this fauna is shown by the following list of species, which were obtained from the north bank of the Porcupine about 5 miles above the entrance to the Lower Ramparts:

Silurian Fossils from the Lower Ramparts, Porcupine River.

Lichenaria cf. *concentrica* Hall.
Favosites cf. *favosus* Goldf.
Columnaria sp.
Alveolites sp.
Diphyphyllum sp.
Zaphrentis ? sp.
Stropheodonta sp.
Strophonella cf. *macra* M. and W.
Leptæna rhomboidalis (Wilckens).
Leptæna cf. *quinquecostata* McCoy.
Leptæna n. sp.
Streptis greyi Davidson.
Dalmanella cf. *elegantula* (Dalman).
Anastrophia cf. *brevirostris* (Sow. ?) Hall.
Stricklandinia sp.
Pentamerus oblongus (Sow.).
Clorinda lingulifera (Sow.).
Camarotœchia cf. *borealis* (Schl.).
Camarotœchia sp.
Camarotœchia neglecta Hall.
Rhynchotreta cuneata Dalm. var.
Atrypa reticularis (Linn.).
Atrypa cf. *calvini* Nettleroth.
Atrypina n. sp.
Cœlospira cf. *clintoni*.
Reticularia cf. *proxima* Kindle.
Spirifer nobilis Barr.
Nucleospira pisiformis Hall.
Meristina nitida Hall.
Meristina sp.
Meristella ? cf. *subundata* McCoy.
Strophostylus sp.
Cypricardinia arata Hall.
Cyrpicardinia n. sp.
Illænus armatus Hall.
Sphærexochus cf. *romingeri* Hall.
Encrinurus sp.
Prœtus, sp.

GRAPTOLITE FAUNA

An exposure near the upper end of the Ramparts indicates the character of the beds near the top of the Silurian series, where shales, which are rare lower in the series, are conspicuous. The beds observed here are shown below:

Section near upper End of Ramparts.

	Feet
Black shale and black to dark gray dolomitic and siliceous limestone	140
Hard siliceous black limestone	12
Black and gray fissile shale interbedded	60
Dolomitic limestone weathering buff, mostly gray on fresh fracture	100

The upper limit of the Silurian series was not observed in the Lower Ramparts. It was recognized, however, 1 mile above the mouth of Salmontrout river, where Devonian limestones overlie the Silurian. This highest bed of the Silurian series consists of fissile black shale and interbedded dark siliceous limestone. Not more than 30 feet of these beds are exposed. Two or three species of graptolites abound in the shale.

This fauna, which is of somewhat later age than the fauna just described, occurs in a black shale at the base of the Devonian section. It was found 1 mile above the Indian village, at Old Rampart House, on the east bank of the Porcupine river. The shale, which is about 25 feet thick, contains some thin bands of black siliceous limestone. About 325 feet of Devonian limestone follows the shale in the section. Graptolites occur in one or two beds of the shale in abundance. Associated with them are a very few brachiopods. This graptolite fauna was referred to Mr E. O. Ulrich, who finds the state of preservation not perfect enough to permit of specific determination. He considers the fauna of "either late Niagaran or Cayugan" age, and reports the following faunal association:

Silurian Fauna, Upper Ramparts

Monograptus sp. undet.
Cyrtograptus sp. undet.
Orbiculoidea.
? *Camarotœchia*.
? *Uncinulus*.
? *Sieberella* (a small species of pentameroid shell possibly of this genus).
? *Rafinisquina* (a very small concentrically wrinkled species).
? *Uncinulus*.
Spirifer cf. *radiatus*.
Dalmanella.

Graptolites have been found at but one other locality in Alaska. In the Mount McKinley region Brooks and Prindle[8] found graptolites which Schuchert referred to three species:

Climacograptus bicornus Hall.
Climacograptus sp. undet.
Decranograptus cf. *ramosus* (Hall).

These represent a fauna much older than the Old Rampart graptolites which Schuchert considered to mark a horizon about equivalent to the Utica of the Ordovician.

Graptolites have been reported from only two localities in the western part of the Dominion of Canada. Both of these are in British Columbia. Neither of the genera found in the Old Rampart fauna is present in the

[8] An exploration in the Mount McKinley region. Bulletin of the U. S. Geological Survey, 1906. (In preparation.)

graptolite faunas at Dease river[9] and Kicking Horse pass,[10] British Columbia, which are referred to the Middle Ordovician by Lapworth.

DEVONIAN LIMESTONE

The lowest division of the Devonian is a limestone formation about 325 feet in thickness. It is a massive light gray to blue limestone weathering buff and considerably broken by joints. It rests apparently unconformably on the graptolite shales described above and is followed in the section by brown shale. The lower 5 feet of this shale may be seen resting directly on the limestone on the bank of the Salmontrout river just above its mouth. The total thickness of this shale is unknown, but, judging from the covered slope extending upward from the limestone along the Salmontrout river, it probably amounts to several hundred feet. Outcrops of the limestone described occur on both banks of the Porcupine immediately above the Salmontrout river, and it is proposed to call this formation the "Salmontrout limestone," from the Salmontrout river, which is the nearest geographic feature having a name available for a formation name. Fossils are abundant throughout this limestone. Its strike and dip are concordant with that of the subjacent Silurian shale and limestone, and afford no evidence of deformation at the close of Silurian sedimentation.

Although no angular unconformity is shown in the relations of the Silurian and Devonian series where observed, unconformable relations between the two are attested both by the lithology and the faunas. In passing from the Silurian to the Devonian, the lithologic change is an abrupt transition from black shales to very pure limestones. The faunal change is from a Silurian graptolite fauna to a Middle Devonian fauna, the Lower Devonian fauna being absent. The Devonian limestone forms a continuous outcropping cliff 100 to 200 feet high for 1 mile above the Salmontrout river, along the east bank of the Porcupine. It also outcrops on the opposite side of the river in isolated exposures.

DEVONIAN FAUNA

The fauna occurring in the Devonian limestone is indicated by the following list:

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[9] Lapworth: Note on graptolites from Dease river, British Columbia. Canadian Record of Science, vol. 3, 1888, pp. 141-142; Geological Magazine, third dec., vol. 6, 1889, pp. 30-31.

[10] Lapworth: Fossils of Kicking Horse pass. Science, vol. 9, 1887, p. 320.

Devonian Fossils obtained opposite Site of Old Rampart House

Favosites sp.
Favosites cf. *hemisphericus* Milne-Edwards and Haime.
Acervularia sp.
Cyathophyllum cf. *quadrigeminum* Goldf.
Crinoid stems.
Crania sp.
Stropheodonta cf. *variabilis* Calvin.
Stropheodonta cf. *arcuata* Hall.
Stropheodonta cf. *calvini* Miller.
Stropheodonta n. sp.
Stropheodonta cf. *armata* (Barr).
Pholidostrophia cf. *iowensis* (Owen).
Leptœna rhomboidalis (Linn.).
Schuchertella chemungensis var. *arctistriatus* (Hall).
Schuchertella sp.
Dalmanella sp.
Camarophoria ? sp.
Gypidula cf. *galeatus* Dalm.
Camarotœchia sp.
Pugnax cf. *pugnus* (Martin).
Eunella sp.
Atrypa reticularis (Linn.).
Atrypa aspera Scholtheim.
Atrypa cf. *flabellata* Goldf.
Retzia cf. *eudora* var. *princeps* (Barr.).
Nucleospira cf. *concinna* Hall.
Parazgia sp.
Spirifer sp.
Spirifer cf. *divaricatus* Hall.
Spirifer sp. (of sp. *raricosta* type).
Spirifer sp.
Reticularia cf. *franklini* Meek.
Reticularia fimbriata (Con.) var.
Cyrtina cf. *hamiltonensis* Hall.
Cyrtina n. sp.
Cyrtia ? cf. *britanicum* (Whid.).
Anoptotheca sp.
Actinopteria near *perstrialis* Hall.
Cypricardinia indenta Conrad.
Megambonia n. sp.
Conocardium sp.
Sigaretus ? n. sp.
Strophostylus sp.
Platyceras cf. *protei* Oehlert.
Platyceras cf. *conicum* Hall.
Platyceras cf. *thetis* Hall.
Platyostoma cf. *naticoidea* Roemer.
Aclisina sp.
Tentaculites sp.
Cyphaspis sp.
Lichas ? sp.
Prœtus cf. *haldmani* Hall.
Prœtus cf. *crassimarginatus* Hall.
Prœtus cf. *phocion* Billings.

The above list is submitted on an approximate and provisional determination of the species preliminary to a full description of the fauna. It seems to justify the following conclusions regarding the fauna: There are present in it several species which are either closely allied to or identical with species which first appear in the better known American sections at a Middle or Upper Devonian horizon. Since characteristic Lower Devonian species appear to be absent from the fauna, its age seems to be either Middle or Upper Devonian. The list contains some species not known below the Upper Devonian in the United States. One of the best known of these is a variety of *Pugnax pugnus*, a species which ranges from the Rocky mountains to New York state and into the Mackenzie River district. *Stropheodonta arcuata* and *S. calvini* are also known to have a wide distribution in the Upper Devonian. *P. pugnus* and *S. arcuata* first appear in the New York section at the horizon of

the Ithaca fauna. Associated with these Upper Devonian forms we find several species characteristic of Middle Devonian horizons. Among these are *Pholidostrophia* cf. *iowensis, Cyrtina* cf. *hamiltonensis, Schuchertella chemungensis* var. *arctostriatus, Reticularia fimbriata, Nucleospira* cf. *concinna,* and species resembling the European forms *Gypidula* cf. *biplicatus* and *G.* cf. *galeatus.* Two possible explanations of this association of Middle and Upper Devonian species in the same fauna present themselves. It has been shown by Williams and Kindle that Middle Devonian species sometimes persist till late Devonian time and appear in certain New York sections associated with Upper Devonian species.[11] It appears most probable, however, from what we know of the relations of *Pugnax pugnus* and its associated fauna to the Upper Devonian of New York, that the occurrence of Upper and Middle Devonian species in the same fauna at Old Rampart is not the result of late persistence of the earlier fauna. This species evidently migrated into the New York province from the northwest in Upper Devonian time. The two significant facts of its association with Middle Devonian fossils in an Alaskan fauna and its abrupt appearance in an Upper Devonian fauna in the United States, taken together, point very strongly to the probability that intercommunication between the eastern Alaska province and the interior American province was cut off during Middle Devonian, but became free about the beginning of Upper Devonian time, when conditions became favorable for the dispersal and migration of such forms as were adapted to it. Some of the species which had during Middle Devonian time been confined to this northern basin spread southward and helped to give a distinctive character to the Upper Devonian fauna as we know it in the United States. This appears to be the probable explanation of an association of species which upon casual examination seems to afford contradictory evidence as to the age of the fauna. If correct, the horizon represented is Middle Devonian.

DEVONIAN SHALE AND IGNEOUS SERIES

The Devonian limestone outcrops on both sides of the Salmontrout river near its mouth. Brownish colored shales overlie the limestone here and extend apparently to the top of the high ridge lying to the south of the stream and represent a thickness of several hundred feet. No fossils were found in these shales, but they are supposed to represent the Upper Devonian.

They are considered to be of Upper Devonian age, because their relation

[11] American Journal of Science, vol. 13, 1902, p. 429.

to the Devonian limestone is similar to that held by shales holding Devonian fossils along the Yukon river. Carboniferous beds replace the Devonian outcrops along the Porcupine about 1 mile below the Salmontrout river. These seem to be of Upper Carboniferous age. Evidence of faulting which appears on the north bank of the river here indicates that the Lower Carboniferous and perhaps a portion of the Upper Devonian may be concealed by a fault. The horizon of the brown shale appears locally to be largely occupied by beds of basalt representing old sea-bottom outflows during the Upper Devonian.

The shale series which terminates the Devonian probably has a considerable thickness, though no estimate can be made from the exposures mentioned, because the thickness exposed to view is probably reduced by a fault lying to the southwest of the Salmontrout river.

The shale horizon appears to be occupied locally by basalt flows of late Devonian age. A considerable thickness of such beds, which are believed to be of Devonian age, forms the lower end of the Upper Ramparts. This rock is a close-grained, dark greenish to black rock, showing bedding planes. These strike about north and south and dip east at about 40 degrees for nearly half a mile above Redgate. Near the top of this igneous series a belt of sedimentary rocks is sandwiched into the basalts, showing the following beds:

Section one-half Mile above Redgate

	Feet
Gray limestone	4
Red and green shale	14
Brecciated limestone with included masses of shale	8
Light gray limestone	35
Red shale	30

Two or 3 miles west of the Coleen river the basalts occur again. Here they overlie a considerable thickness of drab and pale red shales. Black shales are interbedded with the upper belt of basalt at this point.

CARBONIFEROUS SHALES AND LIMESTONES

The outcrops of the Devonian limestone below the Salmontrout river are followed immediately in the exposures of the river bank by outcropping Carboniferous shales. As a result of faulting, however, these exposures appear to represent an Upper Carboniferous horizon.

The Lower Carboniferous is represented by a series of shales and thin beds of limestone, which outcrop between the lower end of the Lower Ramparts and the Indian village. The character of the lowest beds of

this section is shown by the following section, exposed on the north bank of the river about one-fifth of a mile below the Ramparts:

Section one-fifth Mile below Lower Ramparts

	Feet
f. Black shale and thin bands of sandstone (top)	55
e. Dark, nearly black, tough, calcareous shale, with occasional bands of limestone	50
d. Black fissile shale	20
c. Thin-bedded sandstone and shale	15 +
b. Covered	100 ?
a. Black shale	25

The resemblance of this section to the Carboniferous of the Calico Bluff section on the Yukon river is seen in the alternating black shale and limestone of *e*, which is the most characteristic feature of the Calico Bluff beds.

The beds outcropping just above the Indian village also belong to the Lower Carboniferous series, as shown by their fossils, but lie a little above the section just given. Thin bands of limestone alternating with shales likewise characterize this portion of the section, as shown in the following described beds:

Section just above Indian Village

	Feet
b. Bluish gray to blackish sandy shale, drab at base and locally rather fissile (top)	200 +
a. Tough, gray, sandy shales, with 6-inch bands of limestone at intervals of 5 to 10 feet	50

Opposite the Indian village several hundred feet of black Carboniferous slates outcrop on the south bank of the river.

Interbedded quartzites and shales characterize the Carboniferous beds which form the westernmost bedrock outcrops on the river.

Upper Carboniferous horizons are represented, according to Doctor Girty's determinations of the fossils, by most of the Carboniferous limestone and shales occurring east of the Lower Ramparts. The most extensive bed of Carboniferous limestone observed occurs 4 miles above the Coleen or Succor river. The blue limestone beds exposed here are probably 200 feet or more in thickness. They are overlain by fissile black and tough drab shales. The whole mass is embraced in a partially overturned fold, which makes impossible the measurement of the thickness of the beds. This limestone, although classed as Upper Carboniferous, has a different fauna and belongs at a somewhat lower horizon than the limestone of Nation river.

The Carboniferous and Devonian series have not been seen in contact in any of the Porcupine River exposures, so that their relations are not known from actual observation. They are probably conformable, however, as they are in the Yukon River section. It is not definitely known by what beds the Carboniferous series are succeeded. Careful examination of the section has failed to discover any evidence of the presence of beds of Mesozoic age, and they are believed to be absent. The only beds of Paleozoic age which have been observed in contact with the Carboniferous rocks are lavas, probably of Tertiary age, which overlie them unconformably.

CARBONIFEROUS FAUNAS

Doctor Girty's report on the several faunules from the Porcupine Lower Carboniferous as developed below the Upper Ramparts is as follows:

"This fauna appears to be closely related to that obtained on the Yukon at Calico bluff, and I believe that the beds containing them may be correlated. This Porcupine fauna, somewhat more than the other, contains suggestions of the earlier faunas of the Mississippian, and it appears possible that the whole of Mississippian time is represented. The following lists show the species occurring in this group:

Stations between Indian Village and Lower Ramparts

No. 28:

Zaphrentis sp.
Chonetes sp.
Productus aff. *cora* D'Orbigny.
Productus aff. *concentricus* Hall.
Productus sp.
Spirifer aff. *bisulcatus* Sowerby.
Spirifer sp.
Martinia sp.
Aviculipecten sp.
Euomphalus sp.
Ostracoda undet.
Griffithides ? aff. *bufo* Meek and Worthen.

No. 28A:

Productus n. sp.
Spirifer aff. *bisulcatus* Sowerby.
Martinia sp.
Reticularia aff. *setigera* Hall.
Pugnax aff. *missouriensis* Shumard.
Pugnax ? sp.
Dielasma sp.

No. 28B.

Productus aff. *setiger* Hall. ?

No. 30B:

Zaphrentis 2 spp.
Syringopora sp.
Schuchertella aff. *lens* White.
Chonetes aff. *illinoisensis* Worthen.
Productus semireticulatus Martin.
Productus aff. *alternatus* Norwood and Pratten.
Spirifer aff. *bisulcatus* Sowerby.
Rhynchonella sp.
Conocardium ? sp.
Phillipsia sp.

No. 30F:

Orthis ? sp.
Chonetes aff. *illinoisensis* Worthen.
Productus ? (possibly aff. *P. hirsutiformis* Walcott).
Leiorhynchus ? aff. *mesicostale* Hall.
Rhynchonella ? aff. *eurekensis* Walcott.
Ostracoda undet.

Station opposite Mouth of Coleen River

No. 33:

Fucoidal markings.
Euomphalus aff. *subquadratus* Meek and Worthen. ?"

The fossils from lots 28 to 28B are from the Indian village section shown on a preceding page.

The suggestion of the presence of representatives of the early Mississippian fauna which Girty finds in the invertebrate fauna listed above is supported by the evidence of the fossil plants which were obtained a few miles below the stations represented by the preceding fauna, at the first rock outcrops encountered in ascending the river. Dr David White's report on these plants is introduced here as bearing on the age of the Carboniferous rocks below the Lower Ramparts of the Porcupine:

"The collection transmitted by Doctor Kindle contains several small fragments of a fern, *Sphenopteris frigida* Hr.; several pieces of a large fern rachis of unknown generic identity; small rootlets probably belonging to *Stigmária;* and a single very fragmentary and obscure example of *Lepidostrobus.*

"The material is insufficient for the satisfactory determination of the age of the beds, but if the identification of the *Sphenopteris* is correct, the species points strongly to a position in the lower part of the Lower Carboniferous, and probably the basal member of the Mississippian. On account of the distribution of this fern in the Arctic region near the base of the Mississippian, it seems probable that the discovery of additional fossils will prove the beds to belong to that horizon."

The lithologic characteristics of the beds yielding the plant fossils is shown in the following section, number 27:

Section at first Outcrops on the Porcupine above Fort Yukon

	Feet	Inches
i. Quartzite and sandstone, with some interbedded gray shales...	40	..
h. Hard, bluish gray, siliceous shale	10	..
g. Gray quartzite	30	..
f. Black graphitic shale	3	..
e. Buff to creamy white fireclay	..	20
d. Sandstone	..	5
c. Buff, fine-grained fireclay	1	..
b. Black, soft graphitic shale	6	..
a. Thin-bedded gray quartzite, weathering brown (base)	15	..

In the Upper Ramparts, some 40 miles east of the lower stations just described, a belt of Carboniferous rocks occurs holding a fauna which Girty considers to represent a later fauna than that found lower down the river. His report on this fauna follows:

"This fauna, as before noted, presents a different facies from that just listed; but while I have compared many of its species with the Gschelian fauna, it presents a decidedly different aspect from the Nation River material of the Yukon section which I have called Gschelian. On the paleontologic evidence I would regard this fauna, at least the characteristic lots, such as 39A, as Upper Carboniferous and younger than the other group of Porcupine localities. It recalls to some extent the earlier Upper Carboniferous faunas of the New Mexico section, but whether a correlation would be justified upon the broader grounds of more extensive collections and more detailed comparisons I am not prepared to surmise. The lithologic and stratigraphic evidence it appears tends to place at about the same horizon the strata which furnished these two groups of collections, but at present the faunal difference seems to be such that the course either of uniting or of separating them should not be taken unreservedly. The following lists show the species discriminated in the collections to which these remarks apply:

Stations in the Upper Ramparts of the Porcupine

No. 34:

Fenestella sp.
Stenopora sp.
Derbya ? sp.
Productus aff. *gruenewaldti* Krotow.
Productus aff. *popei* Shumard.
Productus aff. *semireticulatus* Martin.
Productus aff. *punctatus* Martin.
Spirifer sp.
Rhynchonella sp.
Aviculipecten sp.

No. 35A:

Productus aff. *cora* D'Orbigny.
Productus aff. *tartaricus* Tscherny, 2 spp.

No. 35C:

Clysiophyllum sp.
Productus aff. *timanicus* Stuckenberg.
Spirifer sp.
Parallelogoceras ? sp.

No. 36:

Sponge.
Crinoidal fragments.
Chonetes aff. *permianus* Shumard.
Productus aff. *aagardi* Toula (not the same as at Nation river).
Productus aff. *timanicus* Stuck.
Marginifera aff. *wabashensis* Norwood and Pratten.
Spirifer aff. *rectangulus* Kut.
Squamularia aff. *guadalupensis* Shumard.
Ambocœlia n. sp.
Pugnax aff. *rockymontanus* Marcou.
Aviculipecten sp.
Conularia sp.
Pleurotomaria, 2 spp.
Euphemus aff. *carbonarius* Cox.

No. 37C:

Cleiothyris ? sp.
Aviculipecten aff. *rectilaterarius* Cox.
Aviculipecten aff. *eurekensis* Walcott.
Pteria ? sp.
Ostracod undet.

No. 39A:

Lingula sp.
Derbya sp.
Chonetes aff. *platynotus* White.
Productus aff. *gruenewaldti* Krotow.
Productus aff. *wallacei* Derby.
Productus aff. *cora* D'Orbigny.
Productus aff. *Humboldti* D'Orbigny.
Productus aff. *humboldti* D'Orbigny. ?
Spirifer aff. *cameratus* Martin.
Spirifer aff. *schellwieni* Tscherny.
Hustedia aff. *meekana* Shumard.
Seminula aff. *mexicana* Hall.
Rhynchopora sp.
Dielasma aff. *millepunctatum* Hall.
Aviculipecten sp.

No. 39A bis:

Euomphalus sp.

No. 39D:

Zaphrentis sp.
Chonetes sp.
Productus aff. *aagardi* Toula (same as No. 36).
Spirifer aff. *rectangulus* Kut.
Squamularia aff. *guadalupensis* Shumard.
Ambocœlia sp.
Rhynchonella ? sp.
Macrodon sp.
Pleurotomaria ? sp."

EXTENT OF THE CARBONIFEROUS IN NORTHERN ALASKA

The stations which Doctor Girty reports to show an Upper Carboniferous fauna (39A and 39C) are located between the lower end of the Upper Ramparts of the Porcupine and the elbow of the river 1 mile below the mouth of the Salmontrout. Girty's conclusion that the fauna is Upper Carboniferous and younger than the other Porcupine Carboniferous stations is in harmony with the observed stratigraphy. The stations represent a practically continuous belt of Carboniferous shales and limestones, except where interrupted by the post-Paleozoic basalts, about 5 miles wide along the river, which is separated from older beds on each side by faults. Evidence of faulting may be seen on the east side of this belt just below the Indian village, on the north bank of the river, and on the west side at the last outcrop of the Carboniferous series. The beds on the east side of this belt are known to be Devonian, and those on the west side are believed to be Devonian also. This Carboniferous series, according to Doctor Girty's determinations, represents a portion of the

Pennsylvanian and seems to be the latest Paleozoic horizon which appears in the Porcupine section.

TERTIARY BEDS

Beds of Tertiary age occupy a broad north and south belt between the Lower and Upper Ramparts, except where the higher parts of the old eroded masses of Paleozoic rocks project up through them. The north and south extent of this basin, which is called the Coleen basin, after the river draining its northern portion, is unknown. The Porcupine traverses this basin in wide sweeping meanders. The migration of the channel of the river along parts of its course through the basin has left in places low banks bordered by recent silts. The westernmost exposures of the Tertiary beds abut against Paleozoic rocks probably of Silurian age a couple of miles below Coleen river. The exposure here shows the following section:

Section of Tertiary Beds below Coleen River

	Feet	Inches
d. Green, loosely consolidated, lumpy clay, with numerous disseminated green and a few black shale fragments	50	..
c. Green marl	..	20
b. Lignite and interbedded dark shales	14	..
a. Dark drab clay and shale, with abundant black shale pebbles..	50 +	..

Loose fragments of lignite from this and other similar beds may be seen on the river bars for 100 miles below it. The beds here dip northeast 20 degrees and strike north 20 degrees west. Elsewhere along the river the Tertiary beds are horizontal. No fossils were found below the Coleen river, but higher up the stream Tertiary invertebrates were found. These more easterly outcrops are well exposed on the largest meander in this portion of the river, known as the Fishhook bend, which shows continuous bluffs for 2 or 3 miles, 40 to 100 feet high, composed mainly of finely laminated shale or clay. The dominant color of these beds is light lemon yellow, which is varied by patches of yellowish green, pink, and brownish. At the upper end of Fishhook bend, on the west bank of the river, the following section was measured:

Fishhook Bend Section

	Feet
e. Fine sand, soil, and muck (top)	1–5
d. Coarse gravel and sand	10
c. Dark carbonaceous clay and old forest bed	0–2
b. Coarse gravel and sand	15
a. Soft, finely laminated, drab-colored clay shale, with large ironstone concretions in upper part, containing fresh-water bivalves	70

The fossils which were secured from the ferruginous concretions occurring in division 5 of the section were referred to Dr W. H. Dall, who reports that "one resembles *Unio onariotes* Mayer from the Kenai formation, another *Anadonta athlios* Mayer of the same beds, but they are probably not identical. The beds are probably Oligocene or Upper Eocene, like those of Kenai."

Considerable interest attaches to these fossils in connection with their bearing on the distribution in Tertiary times of the *Naiades*, a group of fresh-water lamellibranchs represented in the present streams and lakes of lower latitudes in North America by several hundred species.

Maddren and McConnell have reported two basins similar to the Coleen, but larger, higher up the Porcupine a short distance east of the International boundary. One of these has an approximate length of 100 miles and a width of 60 miles. No fossils were obtained by McConnell from these upper basins, but the description which he gives of the beds exposed corresponds so closely to the sections observed by the writer that it is highly probable that the age of the beds in the basins on the two sides of the boundary is the same. McConnell[12] expressed a similar opinion concerning the equivalence of the beds in question, but presented no paleontologic evidence of the age of the beds in either of the basins which he described.

LAVAS

In the Upper Ramparts the Porcupine has cut its gorge for a considerable distance through an extensive sheet of lava. This lava sheet extends from a point 10 miles below the International boundary nearly to the lower end of the Upper Ramparts as a continuous sheet, except for a break of about a mile below Salmontrout river. .The lava beds rest on a highly irregular surface of Paleozoic rocks. The latter in many places form the lower portion of the gorge walls, while the lavas form the upper. Between the Rapid and Salmontrout rivers the walls of the gorge are in places composed entirely of lava. In this part of the river the lavas have a thickness of not less than 300 feet. The lava sheet is made up of several successive flows. At one point evidence of four successive flows was observed. Several of the successive flows were separated by intervals sufficiently long for the accumulation of soil and forest growth. This is shown by the following section, taken near the eastern margin of the sheet:

[12] R. G. McConnell: Report on an exploration in the Yukon and Mackenzie basins, Northwest Territory. Canadian Geological Survey, vol. 4, new series, Report D, 1890, pp. 128, 132.

Section 5 Miles East of Campbell River

	Feet
g. Soil and fine sand, with numerous fresh-water shells	2–5
f. Basalt	10
c. Forest bed, dark clay with abundance of blackened wood	2
d. Basalt	18
c. Forest bed with abundance of blackened wood	6
b. White sand and very coarse gravel	20
a. Gray limestone (Paleozoic)	250

The bed of gravel and sand in this section which separates the lavas from the Paleozoic series was observed at various other points in the same position, though apparently much thinner. It is believed that it represents the same horizon as the gravel bed of the Fishhook Bend section. If this supposition is correct, it follows that the lavas are of somewhat later age than the fossil horizon beds of that section, probably Miocene.

GIANT SPRINGS, NEAR GREAT FALLS, MONTANA

The springs are 2 miles east of Great Falls. The view is taken looking northeast across the Missouri river

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GIANT SPRINGS AT GREAT FALLS, MONTANA[1]

BY CASSIUS A. FISHER[2]

(Presented by title before the Society December 31, 1907)

CONTENTS

INTRODUCTION

In the vicinity of Great Falls, Montana, there are some very large springs which present unique geologic features and an interesting question as to the source of the water. These springs, which are locally known as the Giant springs, are located on the south bank of Missouri river, about 3 miles below Great Falls. They have a very large flow of relatively pure water, which appears at the surface through large joint planes in a medium to coarse grained sandstone belonging to the Kootenai (Lower Cretaceous) period. For a short distance on either side of the main spring there are smaller springs flowing from the joint planes, and directly opposite it, in the bed of Missouri river, there is another large spring, which is only apparent during low water seasons.

Previous workers in treating the geology of this region have made only brief mention of the occurrence of these springs. They were first discovered in 1804 by Captain Lewis, of the Lewis and Clark expedition,[3] and in the diary of that early explorer they are described as "the largest fountain in the United States." More recent observers in the field are

[1] Published by permission of the Director of the U. S. Geological Survey.
Manuscript received by the Secretary of the Society May 13, 1908.
[2] Introduced by C. W. Hayes.
[3] Lewis and Clark expedition, 1804-1806. Coues, 4 vols., 1893.

Nettleton,[4] Weed,[5] Calhoun,[6] and others. The investigation of Nettleton was of a hydrographic nature, while that of Weed was mainly for the purpose of obtaining information concerning the geology of the Great Falls coal deposits. The recent work of Calhoun deals with the general glaciation of northern Montana, including the Great Falls district. An interesting feature of this work is the study and tracing out of the modifications in the course of Missouri river caused by glaciation of the region.

Geologic Relations

Great Falls is situated in a plains region about 45 miles northeast of the Rocky Mountain Front range. The geologic structure in this portion of the plains is relatively simple, the surface rocks consisting mainly of sandstone and sandy shale with an occasional limestone bed, all of Lower Cretaceous age. They lie nearly horizontal, the prevailing dips being at a low angle to the north, away from the mountains. The rocks upon close examination are found to be slightly warped into a series of shallow synclines and low anticlines. This structural feature is scarcely perceptible to the casual observer, being only revealed by a careful examination of the beds exposed along the sides of some of the larger valleys. To the south of Great Falls, in the vicinity of Stockett and throughout the foothill zone, the structure becomes more complex, and local folds and minor faults are not uncommon.

Physiographically the region is one of high broad plateaus sloping gradually to the north, away from the mountains. These plateaus are traversed by numerous deep and relatively narrow valleys. The region has been more or less glaciated, and the Cretaceous rocks comprising the surface are in places covered by glacial material deposited by the Keewatin ice-sheet, which covered a portion of this area in Wisconsin time.[7] There is also considerable local glaciation along the base of the Rocky mountains to the west. The continental glacial deposits are usually not conspicuous, especially on the summits of the plateaus, but in the valleys they are very noticeable. The sequence of events in the glacial history of this region as first worked out by Calhoun is about as follows: The Keewatin ice-

[4] E. S. Nettleton: Artesian and underflow investigation. Senate Executive Document no. 41, part 2, pp. 74-78, 1892.

[5] W. H. Weed: Two Montana coal fields. Bulletin of the Geological Society of America, vol. 3, 1892, pp. 301-330.

[6] F. H. Calhoun: The Montana lobe of the Keewatin ice-sheet. U. S. Geological Survey, Professional Paper no. 50, 1906.

[7] F. H. Calhoun: Op. cit.

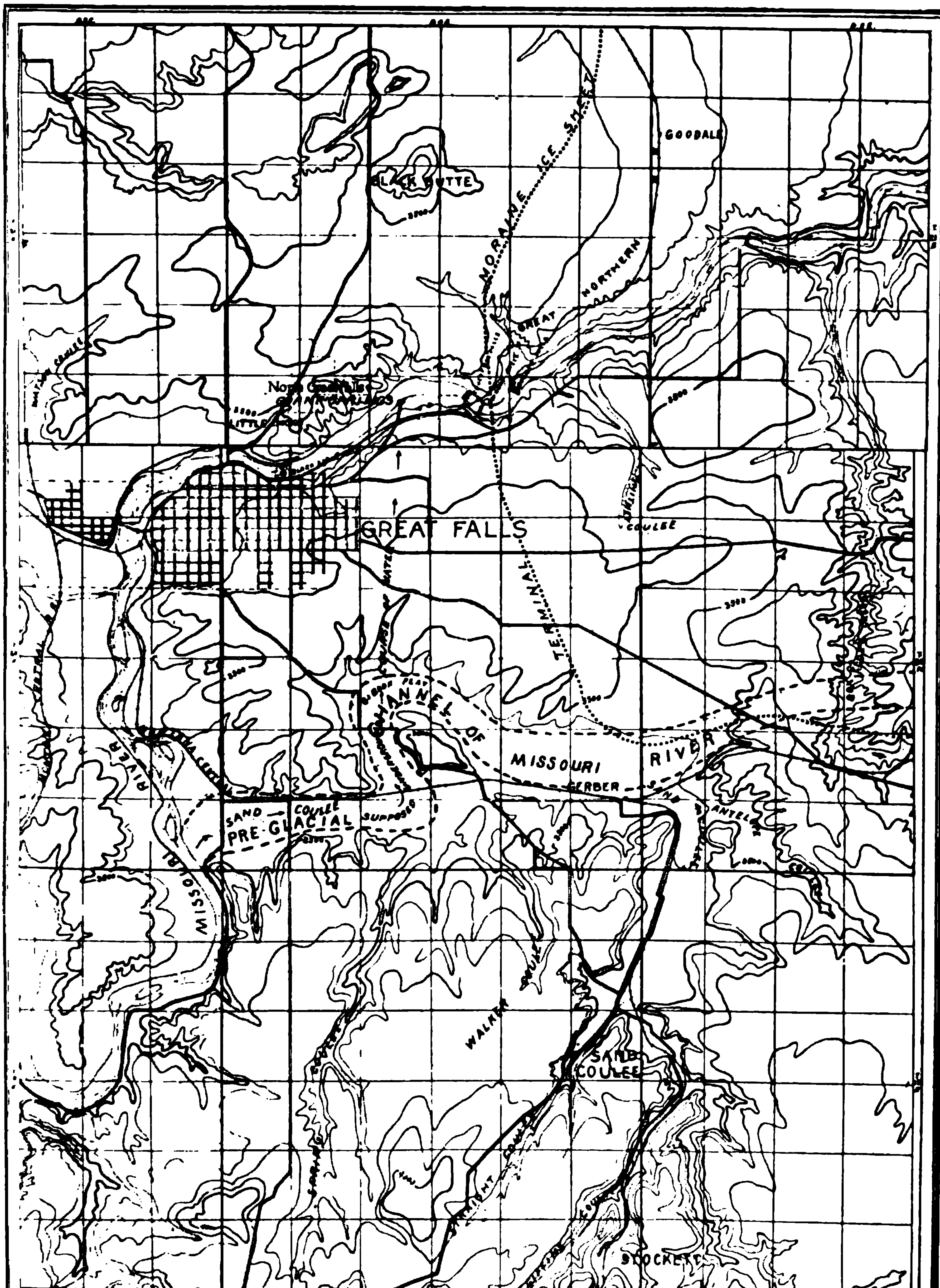

FIGURE 1.—*Map of Great Falls District, Montana.*

Showing pre-Glacial channel of Missouri river and source of Giant springs

sheet extended into the region from the southeast, damming up Missouri river and its tributaries, forcing the former to abandon its channel in many places, some of which were not reoccupied on the retreat of the ice. The abandoned channel, a portion of which is shown on the accompanying map (figure 1), extends from the mouth of Sand coulee, 4 miles south of Great Falls, northeastward in meandering course to the mouth of Belt creek, where it unites with the present Missouri. Missouri river, being obstructed by glacial material, was diverted to the north at the mouth of Sand coulee, passing up Sun River valley for a short distance and then flowing northeastward over Cretaceous sandstone and shale, developing a new channel, along which there are a number of large cataracts or falls. Prior to this diversion, however, while the river channel was occupied by ice, an extensive lake existed in front of the ice-sheet, and boulders, probably deposited by floating ice, are now found high up the plateau slopes to the south and west. After the ice had receded, the terminal moraine acted as a barrier for a lake of much smaller dimension. Sediments were brought into this lake by the Missouri river and its tributaries, filling all of the preexisting valleys of the district, and these filled valleys are a conspicuous physiographic feature at the present time. The relation of the preglacial to the present channel of Missouri river in the vicinity of Great Falls is shown on the map.

Amount of Flow

The fact that the water of the Giant springs issues from rocks at the water's edge and in the bed of the river renders it difficult to measure their exact flow. In order to ascertain this amount, stream gaugings were taken by E. S. Nettleton[8] of the total flow of Missouri river above and below the springs. The difference between these two measurements is assumed to be the quantity furnished to the river by the springs. The total flow of the springs thus obtained is approximately 638 cubic feet per second—an amount which, converted into gallons, is the equivalent of over 400,000,000 gallons every 24 hours—a veritable underground river. It is readily seen from these figures that the springs rank among the largest in the United States. The water boils up with considerable force, is clear, blue, and relatively pure. It contains no more dissolved salts than the average well water of the region, and differs in composition from Missouri River water chiefly in sulphate content, which can be accounted for by the large amount of gypsum in the shale of the Kootenai forma-

[8] E. S. Nettleton: Op. cit., p. 77.

tion, through which it passes. It has a temperature of 50 degrees Fahrenheit.

Utilization

No spring deposits occur in the immediate vicinity of Giant springs. The water is not generally regarded as possessing therapeutic qualities. It is not utilized at present, but is allowed to empty into the river, materially increasing the flow of the stream. There are, however, a few improvements, such as sidewalks, etcetera, which make it possible for tourists to view the springs from the most advantageous points. While no use is now made of this large volume of water, it is so situated that the water could be pumped if necessary to a standpipe in East Great Falls, from which it could be easily distributed to any part of the city. This, however, will probably never be done, for water for city supply can be more economically obtained from Missouri river, a short distance above the town, where the present water works are located. With the development of water power at the Falls of Missouri river below the Springs, and the growth of industrial towns which would necessarily accompany such development, the water of the Giant springs would afford an excellent source of domestic supply.

Composition

A chemical analysis of the water was made some years ago by Professor James A. Dodge, of the University of Wisconsin, and a field analysis was made during the past field season by W. R. Calvert, of the United States Geological Survey. These analyses are given below:

Analyses of the Water of Giant Springs, near Great Falls, Montana

Mineral Analysis

(Grains per gallon)

$CaSO_4$	14.04
$CaCO_3$	4.38
$MgCO_3$	4.98
$NaCl$	.56

Field Analysis

(Parts per million)

Turbidity	0
Color	0
Iron	0
Calcium	142
Total hardness	97.30
Total alkalinity	339.15
Alkaline carbonates	0
Alkaline earth carbonates	339.15
Sulphates	250
Chlorides	9.96

Source of the Springs

The source of the Giant springs has always been a matter of considerable interest to people living in the vicinity of Great Falls, and repeated attempts have been made to tap this water above the springs by sinking deep wells along its supposed underground course.[9] It has been thought by previous observers that the water of Giant springs is of deep-seated origin, and that its source is far from the vent and in the neighboring mountains to the south and west. Such a source is improbable for the following reasons: First, if the water came from a great depth it would have a temperature higher than 50 degrees, and would be expected to be more highly mineralized than is shown by the analyses. Second, the geologic structure of the general region is unfavorable for such a source. Southwest of Great Falls the rocks dip gently to the west toward the mountains, instead of normally away from the uplift. The formation from which the water issues (the Kootenai) in its westward extension passes beneath a considerable thickness of impervious Colorado shales, and in the vicinity of the Big Belt and Lewis ranges, where a large thrust fault occurs, it is buried by many hundred feet of sediments. Under these conditions it is apparent that these porous beds of the Kootenai and strata beneath them are completely sealed off from a surface water supply which might be derived under more favorable structural conditions from melting snow on the mountain slopes.

South of Great Falls, between Giant springs and Little Belt mountains, the geologic and structural conditions, although different from those above described, are equally unfavorable for the occurrence of deep-seated springs anywhere in the vicinity of Great Falls. The general dip

[9] E. S. Nettleton: Op. cit.

of the rocks in this district is north, away from the mountains, toward the plains, but local folding of the strata and erosion on a line between Giant springs and high mountains to the southward exposes beds down to a point about 150 feet below the top of the Madison limestone, thus affording a vent for any water that may accumulate in the upper part of the Madison or in beds overlying throughout their distribution in the higher portions of the Little Belt mountains. While no special examination has been made of the water capacity of the lower part of the Madison limestone, it is believed from a general study of the occurrence of underground waters in this district that it is not a good water bearer.

It has been believed for some time by a few local observers that the water of Giant springs comes from Gibson flat, where a strong underflow is known to exist. Most of these observers are of the opinion, however, that the original source of this water is in Little Belt mountains, and that it comes from that district as an underflow by way of Sand coulee and its various tributaries into Gibson flat, rather than down the preglacial channel of Missouri river from the present stream valley. That the amount of underflow in the upper part of Sand coulee and its combined branches is small and entirely inadequate to supply the Giant springs is shown by a test which was made of the underflow in one of the largest tributaries of this drainage at the town of Stockett. Here a well was dug in the middle of the valley by one of the coal companies, through alluvium to bedrock, and from the bottom of the well tunnels were excavated in either direction to the sides of the valley in order to catch the entire underflow. The maximum capacity of this well is about 125,000 gallons per day, while that of the Giant springs is over 400,000,000.

From a careful study of the geologic relations in the vicinity of Great Falls, it is believed by the writer that the water of Giant springs is derived from the subriver bed of the Missouri, leaving that valley near the mouth of Sand coulee as an underflow and passing down the preglacial channel of the Missouri, which is in reality up Sand coulee, into Gibson flat, an oxbow in the old river channel. From here, by a subterranean passage through porous Cretaceous sandstone and sandy shale, which dip in a favorable direction for its transmission, it makes its escape to the present Missouri river, where it appears in the form of the Giant springs (see plate 20).

It is further believed by the writer that the jointing, which is here well developed with the major joint planes extending in a north-south direction, is an important factor in the underground movement of the water. It is also possible that a fault in this vicinity further facilitates the

underground passage of the water, but no positive evidence of this was seen. Well borings in lower Sand coulee and Gibson flat demonstrate that the materials filling the old valley are largely coarse river sediments well adapted for rapid percolation of water.

From the above it is readily seen that along the supposed underground course of the water from the mouth of Sand coulee to where it appears at the surface as springs, the physical conditions are such as to permit the passage of a large volume of water, an amount believed to be equivalent to that furnished by the Giant springs.

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GLACIAL PERIODS AND THEIR BEARING ON GEOLOGICAL THEORIES[1]

BY A. P. COLEMAN

(Presented before the Society December 30, 1907)

CONTENTS

INTRODUCTION

It is intended in this paper to call attention to certain sides of glacial geology which have a bearing on the broader problems of geology in general, and which should receive consideration from workers in other departments of geology and in the related sciences which deal with the early history of the earth, such as physics and astronomy. Glacial geology will be construed in its widest sense, not as confined to Pleistocene phenomena, but as including glacial activity in all ages where ice has left widespread proofs of its work.

It will be necessary to give a summary of the evidence showing the extent of glaciation at various times in the earth's history; and the question of interglacial periods will be taken up briefly also. Afterward general conclusions will be drawn from the evidence, and these will be used as tests of various theories.

Evidence of ice action on a large scale is, of course, widely available in regard to the Pleistocene ice age, from which the world seems to be just emerging and whose broad effects all geologists admit. Such evi-

[1] Manuscript received by the Secretary of the Society March 25, 1908.

dence is naturally harder to obtain as one goes backward in the geological records, but a late Paleozoic (Permo-Carboniferous) ice age is generally accepted as proved for large parts of the world, and an early Cambrian ice age seems to have left its record in several widely separated regions. There is also strong evidence, as shown in a previous paper in the Journal of Geology, of a Lower Huronian ice age whose effects are found over hundreds of thousands of square miles. These four glacial periods are the most important so far as known, though supposed proofs of ice action have been found in the Cretaceous, the Lower Carboniferous, the Lower Devonian, and at other horizons. In the latter cases the area affected seems to have been only small, and the work may have been done by local alpine glaciers rather than continental ice-sheets, such as left their mark in the four periods mentioned above. It is probable that local glaciers have existed on lofty mountains from the earliest ages, even when the lower regions had a warm climate extending toward the poles; but ice ages imply a much more important refrigeration, reaching low ground in regions now having a temperate or even a tropical climate.

The Pleistocene Glacial Period

One naturally begins an account of ice ages with the last one, which filled most of Pleistocene time and whose ice-sheets still linger in Arctic and Antarctic regions and on high mountains to show us how the work was done.

Briefly summing up the extent of its work, one may say that 4,000,000 square miles of North America were covered by ice-sheets, including the whole of Canada except the Yukon territory and most of the northeastern United States, with a southern limit of latitude 37° 30′ in the Mississippi valley. About half as much territory was ice-covered in northern Europe, the southern boundary being about latitude 53°, and the great mountain ranges of Europe, especially the Alps, were heavily glaciated south of the main sheet.

In Asia there appear to have been no great continental ice-sheets, but in almost all the mountain areas there were glaciers where none now exist, or the glaciers were far more extensive than at present. Lebanon, the Caucasus, the Himalayas, and the mountains of Manchuria all show ice-scored surfaces and moraines, even reaching down to 4,500 feet above the sea in latitude 26° in Bengal, and to 2,000 or 3,000 feet in the western Himalaya.

In Africa the Atlas mountains bore glaciers, and on the lofty peaks

under the equator—Kenia, Kilimanjaro, and Ruwenzori—glaciers advanced thousands of feet lower down than at present.[2]

Mount Kosciusko, in Australia, had glaciers where there are none now. Tasmania's tablelands were ice-clad and sent glaciers down almost to sealevel,[3] and the glaciers of the south island of New Zealand were much longer than at present.

Patagonia was widely glaciated south of latitude 37°, striated rock surfaces, boulder clay, and erratics occurring as in North America, and the ice-sheet reached the sea, while the Andes to the north have even within the tropics old moraines 800 to 900 meters below the end of the present glaciers.

From Scott's "Voyage of the *Discovery*" one learns that the Antarctic ice-sheets are retreating, and that old moraines and striated surfaces give proof of former extension of the ice over shores and islands now left bare of snow in summer.

It is a striking fact that the great continental ice-sheets of the north were very local in their arrangement, all converging about the north Atlantic and its prolongations into Hudson bay, Davis straits, and the Arctic sea north of Russia. The Cordilleran ice of British Columbia, which faced the north Pacific, is hardly an exception, for it consisted really of greatly extended mountain glaciers, confluent in the valleys, above which the higher summits projected. It should be compared with the Alpine glaciation of Europe rather than with the continental type of glaciation.

In the southern hemisphere, so far as known, the whole of the Antarctic continent was ice-covered, but no other large land area was in high enough latitudes to permit ice-sheets to spread out on the lowlands and reach the sea, except in Patagonia.

Lowland ice did not reach nearer to the tropics than about 37° of north and south latitude in the Pleistocene glacial period, though mountains under the equator had much more extensive glaciers than at present. In intensity the Pleistocene ice age seems to have been much surpassed by at least one of the older periods.

The Permo-Carboniferous Glacial Period

The Paleozoic ice age of India, Australia, South Africa, and South America has been the subject of study on the first three continents for the

[2] Gregory in Quarterly Journal of the Geological Society, vol. l, 1894, pp. 327, etc.; Duke of Abruzzi in Geographical Journal, vol. xxix, no. 2, p. 144.

[3] Gregory: Ibid., vol. 60, 1904, p. 52; and Australian Association for the Advancement of Science, vol. ix, 1902, p. 191.

past fifty years, and more recently on the fourth also. A very extensive but much scattered literature has grown up regarding it in Indian survey memoirs and records, Australian and South African survey reports and transactions of societies, in the British and German geological journals, and elsewhere; so that it is a serious labor to bring together the published data. References to most of the literature may be found in articles by Dr David White,[4] Professor Frech,[5] Doctor Noettling,[6] and in several of the reports of the Australian Association for the Advancement of Science.[7] There is also an important discussion of the subject, mainly from the paleontological point of view, by Doctor Koken, which should be consulted.[8]

The widespread development of boulder clay, or "tillite," to use Professor Penck's convenient term, and in many parts also of underlying striated surfaces, in the three continents first mentioned, are as convincing as those of the Pleistocene ice age in North America and Europe.

In India the field geologists of the survey have found boulder conglomerates at many places in the Talchir and Salt range at points 700 or 800 miles apart, the two Blandfords and Doctor Oldham being responsible for much of the work. In 1885 Doctor Griesbach reported conglomerates exactly like those of the Talchir near Herat, in Afghanistan,[9] extending the limit to a distance of 1,500 miles from the most southeasterly outcrop in India. Within the Indian empire the ancient boulder clay occurs from latitude 25° to latitude 16° or 17°, and if Griesbach's discovery is included the northward extension reaches latitude 34° or 35°.

It may be added that the plant beds of the Gondwana associated with the glacial deposits found near Herat are much like beds found in Russian Turkestan and Elburz, in Armenia, suggesting a still farther extension to the west, and that a probably glacial conglomerate is known from the Urals.

In Australia much attention has been given to the Permo-Carboniferous tillite, which has been traced widely in all the states of the Commonwealth,[10] including the island of Tasmania to the south, with a range of latitude between 20° 30′ and 43°. Striated rock surfaces are often found under the old boulder clay, the directions of the scorings indicating

[4] American Geologist, vol. iii, 1889, pp. 299-330; Journal of Geology, vol. xv, 1907, pp. 615-633.

[5] Lethæa Geognostica, theil I, band ii, pp. 579, etc.

[6] Neues Jahrbuch für Mineralogie, band ii, 1896, pp. 61-64.

[7] Hobart: Vol. ix, 1902, pp. 191-204; also vols. vii, viii, and x.

[8] Neues Jahrbuch für Mineralogie, Festband, 1907, pp. 446, 545.

[9] Geological Survey of India, Records, vol. xviii, p. 62.

[10] Australian Association for the Advancement of Science, vol. ix, 1902, pp. 190, etc.

a motion of the ice in general from south to north, as might have been expected; but in various places the ice sheet or sheets reached the sea, large boulders occurring in stratified shale, as if dropped from ice, and marine fossils being found in close connection with the beds containing boulders.

In South Africa the Dwyka tillite has been found in all of the British provinces from the south of Cape Colony to the middle of the Transvaal or possibly the southern boundary of Rhodesia, and from Prieska, in Cape Colony, on the west to eastern Natal. In a direction from southwest to northeast the Dwyka is known to have an extension of about 800 miles, and it probably extends considerably farther north. To the southward the Dwyka reaches nearly latitude 34°, according to Mr Rogers; Doctor Molengraaf puts its northern limit in latitude 26° 40',[11] but Mr Mellor extends it to a point 90 miles north of Johannesburg,[12] about latitude 24° 30', and Mr Mennell speaks of "what is almost certainly Dwyka conglomerates" in the Tuli district of Rhodesia in about latitude 22°.[13]

The direction of the striations so splendidly shown in the northern part of Cape Colony, Natal, and the Transvaal, and of the transport of boulders, is southward—something quite unexpected—and the tillite grows thinner to the north, toward the glacial center, as the Pleistocene boulder clay does in northern Ontario, and thickens to the south, as in the northeastern United States. In the southern part of Cape Colony Mr Rogers estimates its thickness at 1,000 feet, while at the Kimberley diamond mines it is only a few feet thick. Toward the south no striated floor is found under the Dwyka, but the tillite passes downward and upward into stratified shale or slate, suggesting that the ice reached the sea and dropped its load of englacial till on the shallow bottom. Marine fossils have not been found in the shales, however, so that the deposits may have been formed in a huge fresh-water lake.

The Dwyka now occurs at elevations of 3,000 to 6,000 feet at the sea, probably much higher than the level at which much or all of it was deposited, since the southern part was laid down in the sea or great marginal lakes which could not have been much above sealevel.[14]

Judging from my own observations, the northern part of the area covered by the great ice-sheet was not mountainous, but rather a peneplain, like the area covered by our Labrador ice-sheet in Pleistocene times, with hills and valleys, but no high ridges.

[11] Geology of the Transvaal, p. 74.
[12] Quarterly Journal of the Geological Society, vol. 61, 1905, p. 680.
[13] Science in South Africa, p. 302.
[14] See Professor Davis's discussion of the subject, Journal of Geology, vol. xvi, p. 81.

It is worthy of note that the whole area of glaciation in Africa is probably not yet known, since the striations and directions of transport of blocks are *all southward.* It is quite likely that the center of glaciation was north of latitude 25° or even within the tropics, and that the ice flowed out in all directions, north as well as south. The reported finding of a glacial boulder conglomerate by Kört in Togoland suggests that decisive proofs of northward ice movements may yet be found.

The Indian sheet also appears to have moved only in one direction, *northward,* or away from the equator, so far as one can infer from the transport of boulders, since striated surfaces seem rare.[15] Oldham notes that boulders in the Salt Range conglomerate are like rocks 750 miles to the south;[16] and this is confirmed by Koken.[17]

To the three great areas of glaciation within regions now warm temperate or tropical must be added southern Brazil, where Dr Orville Derby and Dr I. C. White have found what they believe to be a glacial conglomerate beneath coal measures.[18] It is noteworthy, as shown by the paleobotanist, Dr David White, and other paleontologists, that all these glacial beds are followed by coal seams and are accompanied by cold climate plants of the *glossopteris* or *gangamopteris* flora, showing that the different regions mentioned were glaciated in the same geological period.[19]

With such tremendous developments of ice action in the southern hemisphere and in India, in regions now so warm, one naturally asks, What occurred at this time in the rest of the world? But the records elsewhere are very meager. In Russia a Permian boulder conglomerate, with the *glossopteris* flora, has been found in the eastern Urals by A. Karpinsky, who believes it to be glacial, while Doctor Tschernyschew would only say that it is probably glacial.[20]

The finding of a supposed glacial deposit of similar age by Ramsay in England in 1855[21] seems to have been disputed by almost all other British geologists, though Oldham, fresh from the Indian region, believes that these boulder beds are probably glacial after all—not true boulder clay,

[15] The only mention of the direction of striæ which I have found is by Medlicot and Blandford, Manual of Geology of India, p. 229, where the motion was northeast by north.

[16] Geology of India, p. 120.

[17] Neues Jahrbuch für Mineralogie, Festband, 1907.

[18] Science, vol. xxiv, no. 612, 1906, p. 377.

[19] Journal of Geology, vol. xiv, no. 2, 1907, pp. 615-633.

[20] Geological Survey of India, Records, vol. xxxi, part 3, 1904, pp. 112-113. (Translated by Professor P. Brühl from Bulletin of Commercial Geology, tome viii, pp. 204-206.)

[21] Quarterly Journal of the Geological Society, 1855, p. 185.

but morainic materials with scratched stones which have been reassorted by water, apparently kame deposits.[22]

In North America a supposed Permian moraine in Prince Edward island has been described and sketched by Mr F. Bain, but no striated stones are mentioned in his account.[23]

Dr Whitman Cross describes and shows a photograph of a boulder conglomerate that strongly suggests glaciation in the Permian (?) Red beds of Colorado, but makes no reference to ice action in his account of the region.[24] It might be worth examining for scratched stones.

As in the Pleistocene, there seems to have been an impressive grouping of the great ice-sheets in a special quarter, this time in the neighborhood of the present Indian ocean; and their nearness to the equator, on low ground and reaching the sea, makes it all the more puzzling that so little evidence of glacial work should be found in higher latitudes.

The early Cambrian Glacial Period

Gradually proofs of an early Cambrian or late pre-Cambrian ice age have been accumulating, and its effects seem sufficiently widespread to be included in the present discussion, since they are found in various places both north and south of the equator. Some of the localities are within the Arctic circle, such as northern Norway[25] and Spitzbergen,[26] where glacial conditions might be expected if the earth then had its climate arranged in zones; but others are in parts of the world now having temperate or warm climates. Among the latter is the glacial conglomerate reported by Mr Bailey Willis from the Yangtzi canyon, latitude 31°, in China, from which beautifully glaciated stones were obtained.[27]

Tillites of this age are, however, much better displayed in the southern hemisphere, in Australia and South Africa. The Australian Association for the Advancement of Science has for a number of years published reports of a committee appointed to examine deposits belonging to ancient ice ages in the different states, and in these reports there are not only accounts of the Permo-Carboniferous tillites, but also descriptions of similar rocks from the basal Cambrian. Mr Howchin has been specially suc-

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[22] Ibid., 1894, pp. 463 to 468.

[23] Canadian Record of Science, vol. ii, 1887, pp. 341-343.

[24] Journal of Geology, vol. xv, 1907, pp. 662-665.

[25] Norges geologiska Undersögelse; Det nordlige Norges Geologi, pp. 26-34, 1891; and Strahan in Journal of the Geological Society of London, vol. liii, 1897, pp. 137-146.

[26] Gregory: Climatic variations. Mexican Congress, p. 7.

[27] Carnegie Institution of Washington, 1907. Research in China, vol. i, part i, p. 267; also Chamberlin and Salisbury's Geology, vol. ii, pp. 273-274.

cessful in tracing these early Paleozoic boulder clays on the Mount Lofty ranges in South Australia. He finds them extending 460 miles from north to south and 250 from east to west, with a thickness of 1,500 feet. Many well striated stones have been obtained from this tillite, which is supposed to have been formed by floating ice at sealevel.[28] The general question of Cambrian boulder clays is discussed by Professor David also, who suggests that the ice reached sealevel, on the evidence of intercalated beds of limestone with what are probably radiolarian shells. The direction of motion was probably from south to north, as shown by inclosed boulders.[29] The Cambrian boulder clay is found also on the west coast of Tasmania. No striated rock surfaces have been reported beneath the Cambrian tillite.

The South African early Cambrian or late pre-Cambrian tillite, belonging to the Griquatown series in Cape Colony, has been examined by Mr Rogers and his assistants and is known to cover at least 1,000 square miles.[30] Some scratched pebbles sent me by the kindness of Mr Rogers are typically glacial.

The South African Cambrian tillite occurs in about latitude 29°, while that of Australia ranges through several degrees of latitude, from Tasmania to latitude 32° or 33°, in South Australia; so that ice action reached considerably nearer to the equator than in the Pleistocene glacial period, but falls much behind the Permo-Carboniferous in this respect.

In North America there are many instances of coarse conglomerates which might be glacial in the Lower Cambrian, or what is probably its equivalent, the Keweenawan; but, so far as my reading goes, only one authority has found striated stones in the boulder conglomerates. Doctor Bell reports boulders reaching diameters of 3 feet 8 inches, having grooves like glacial striæ, in a conglomerate with sandy matrix belonging to the Keweenawan of Pointe aux Mines, near the southeast end of lake Superior.[31] Messrs Lane and Seaman describe a Lower Keweenawan conglomerate as containing "a wide variety of pebbles and large boulders, in structure at times suggestive of till," from the south shore of lake Superior.[32]

[28] Royal Society of South Australia, vol. xxx, p. 227; also American Association for the Advancement of Science, 1902, pp. 190-204; and Nature, December 19, 1907, p. 165. (Report of Geological Survey of South Australia.)

[29] Australian Association for the Advancement of Science, 1902, pp. 199-200.

[30] Transactions of the Geological Society of South Africa, vol. ix, 1906: The Campbell Rand and Griquatown series in Hay., by Rogers, pp. 8 and 9; also Transactions of the Australian Association for the Advancement of Science, 1906, paper 24, The Glacial beds in the Griquatown series; and by Schwartz, Journal of Geology, vol. xiv, no. 8, pp. 683-691.

[31] Geology of Canada, 1876-1877, p. 214.

[32] Journal of Geology, vol. xv, no. 7, p. 688.

In the Australian reports previously referred to, Professor David mentions that rocks of a similar character to the Cambrian tillites, and probably of the same age, occur on Mackenzie river, in Canada, and on the Lena, in Siberia, but I have not been able to find descriptions of these boulder conglomerates.

If the glacial beds referred to above were all formed in the same age, which seems probable, the early Cambrian glaciation extended to both hemispheres in latitudes from 29° to 70°, and, at least in Australia, covered thousands of square miles and reached sealevel in regions now having a warm temperate climate. It is interesting to note that the Cambrian ice age, like that of the Permo-Carboniferous, seems to have been most intense in the southern hemisphere, in Australia and South Africa.

The Lower Huronian Glacial Period

Probably the earliest suggestion of a Huronian ice age was made by Shaler and Davis in their work on Glaciers, where the origin of some of the conglomerates is described as probably glacial.[33]

Sir Archibald Geikie states of certain Archean boulder beds in Scotland that "where the component blocks are large and angular, as at Gairlock, they remind the observer of the stones in a moraine or in boulder clay."[34]

The first recorded striated stones of Huronian age have been found within the past two years in the Cobalt silver mining region of Ontario by the present writer, the earliest account of the Lower Huronian tillite having been published in the American Journal of Science for last year.[35] A much fuller treatment of the subject, with photographs of tillite, striated stones, etcetera, has appeared in the Journal of Geology, and for details the reader may be referred to that article.[36] With the exception that no striated rock surfaces have yet been found beneath the Lower Huronian tillite, all the varieties of evidence depended on to prove the glacial origin of the Permo-Carboniferous apply perfectly to this most ancient glacial deposit. Specimens of the boulder clay from the two horizons are almost indistinguishable in hand specimens or in thin sections under the microscope.

How suggestive these boulder conglomerates are of glacial work is shown in accounts prepared by geologists who hesitate to draw the same

[33] Glaciers, p. 101.
[34] Text-book of Geology, p. 705.
[35] American Journal of Science, vol. xxiii, 1907, pp. 188-192.
[36] Vol. xvi, pp. 149-158.

conclusions as the present writer. Professor Miller, who has mapped the Cobalt region, calls attention to the resemblance of the rock to boulder clay, since "the granite boulders are often 2 or 3 feet or more in diameter and distant a couple of miles from exposures of the rock."[37] Professor Brock, who has described the gold-mining region of Larder lake, in the same formation, but 20 miles farther north, gives the following account of the rock:

> "The thickness and widespread extent of the conglomerate in northern Ontario, where its general characteristics seem to remain constant throughout, the clean-swept and often rounded surfaces of the older rocks on which it is frequently laid down, and the extraordinary variation in the size of the boulders—these and other facts stated above regarding the conglomerate of Larder lake furnish the strongest evidence yet found for a glacial origin. But there are still difficulties in the way of its acceptance. The deposits can not be said to have the appearance of glacial deposits. There has been no boulder clay recognized—the material has been at least resorted."[38]

If Professors Miller and Brock had been familiar with ancient glacial deposits, such as the Dwyka in South Africa, they would no doubt have taken a different view of the matter, since the Cobalt conglomerates are exactly like the more consolidated varieties of the Dwyka conglomerate. That some of the matrix shows hints of stratification is, of course, not an argument against a glacial origin, for Pleistocene boulder clays and kame deposits often show the same mixture of ice-formed and water-laid materials.

The vast extent of the Lower Huronian conglomerate is only explicable by glacial action. In the east, near lake Chibougamou, Richardson described such a conglomerate, with boulders tons in weight, many years ago;[39] and similar conglomerates occur in every Huronian area mapped in northern Canada through a region 1,000 miles long from east to west and 750 miles broad. The only similar boulder-bearing formations known are the Permo-Carboniferous and Pleistocene boulder clays, the Lower Cambrian beds being apparently much less extensive; and those who object to the interpretation should explain how these boulder beds hundreds of feet thick, stretching over hundreds of thousands of square miles, were formed if not by the action of land ice.

Interglacial Periods in the Pleistocene

The four great glacial periods briefly outlined above are generally

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[37] Bureau of Mines, Ontario, 1905, p. 41.
[38] Ibid., vol. xvi, part 1, p. 212.
[39] Geological Survey of Canada, 1870-1871, pp. 293-294.

thought of as units, though there is reason to believe that they were interrupted by warmer interglacial periods. There is, however, much diversity of opinion in regard to the importance of these interglacial episodes, some geologists, such as Professor Wright and Mr Warren Upham in America, Mr Lamplugh in England, and Doctor Geinitz in Germany, minimizing their importance; while others hold that in one or more interglacial periods of the Pleistocene the ice-sheets were completely removed, to be reformed later.

The evidence for at least one interglacial period in northeastern America, with a complete disappearance of the ice and a climate several degrees warmer than the present, seems to the present writer absolutely convincing. Those who wish to follow up the matter in detail will find the evidence in various reports of a committee of the British Association[40] on the Toronto formation, and in a paper read by the present writer before the Mexican Geological Congress.[41] The importance of the Toronto interglacial formation is very well shown also in Chamberlin and Salisbury's Geology.[42] Here it is unnecessary to do more than call attention to the more salient points in connection with this interglacial period.

The interglacial deposits began after the ice had retreated some hundreds of miles, to a point far to the north of Toronto, and after streams had cut channels through the boulder clay into the underlying rock. The beds laid down on the eroded surface contain leaves and wood of a rich forest, including an assemblage of trees which now grow 150 miles farther south. There were also unios which are not now found in Ontario, but inhabit the Mississippi. A great river flowing from the north into the rising waters of an interglacial lake Ontario built up a delta 180 feet thick and 25 miles wide. The interglacial lake was drained and wide river valleys were excavated to a depth of more than 150 feet. Finally the ice covered the region again, burying the whole formation under thick sheets of boulder clay which extend hundreds of miles southwest of Toronto.

Interglacial beds with wood, peat, and brown coal are found on the Hudson Bay slope also, showing that the surface was free from ice 400 miles north of Toronto.

From the series of events just outlined it can hardly be doubted that this interglacial period lasted for tens of thousands of years, during which

[40] Canadian Pleistocene fauna and flora, 1898-1899 and 1900.
[41] Interglacial periods in Canada.
[42] Vol. iii, pp. 490-493.

the Labrador ice-sheet must have completely vanished. It may be added that the Labrador sheet was the largest known in the Pleistocene ice age.

The strong proofs of important interglacial periods in the states to the south, brought forward by Professor Calvin and others, reinforce the evidence from Ontario; and the same is true of the western states, where Mr W. W. Atwood demonstrated the occurrence in the Uinta mountains of two glacial periods separated by a long interglacial time.[43]

It is interesting to find this evidence corroborated from the Andes in South America, as shown by Dr Hans Meyer, who has found two great extensions of the ice separated by a long interglacial period in Equador;[44] and by Professor Tight, who found proofs of no less than three interglacial periods near Ilimani and Sorata, in the Bolivian Andes. From Patagonia also Doctor Moreno reports two ice ages and an interglacial period in which neo-mylodon existed.[45]

In Europe Professor Penck and others have demonstrated several interglacial periods in the Alps, while Dr James Geikie makes a strong case for as many interglacial times in Great Britain and northern Europe.[46] To what extent Mr Lamplugh[47] and Doctor Geinitz[48] have invalidated his arguments the present writer can not venture to decide.

Doctor Bogalübow's account of an important interglacial period in central Russia lasting, as estimated, from 12,000 to 20,000 years, and including an earlier time of forest growth and a later one of steppe conditions, can hardly be brushed aside as of no weight.[49] In Australia, too, the glacial deposits on mount Kosciusko are of two ages, with an interglacial period between.[50]

It should be kept in mind that negative evidence is of very little value as compared with positive evidence in a matter of this kind, since all records of an interglacial period are apt to be swept away by the oncoming of later ice-sheets. This is particularly true in the central areas, where the surface is often scoured bare to the solid rock. Interglacial deposits at any distance within the margin of the ice can only be preserved under special conditions, such as the filling of an old river or lake valley or the

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[43] Journal of Geology, vol. xv, no. 8, pp. 795, etc.

[44] La Geographie, vol. xv, no. 1, p. 62, In den Hoch Anden von Equador. (Review.)

[45] Royal Geographical Journal, vol. xiv, pp. 368-370.

[46] The Great Ice Age.

[47] British Association, 1906, pp. 532-558.

[48] Neues Jahrbuch für Mineralogie, Beilage, band xvi, 1903, pp. 1-98.

[49] Zur geologischen Geschichte des Gouvernements Kalugo in der Glazialperiod. Moscou, 1905.

[50] Australian Association for the Advancement of Science, 1902, p. 204.

piling up of great delta masses of firm materials which the later ice-sheet can not displace, but must climb over.

The absence of interglacial deposits in any given region is, then, no valid argument against interglacial periods. The writer holds that at least one interglacial period of great length and with a warm climate is proved for America, and that there is evidence enough in the rest of the world to suggest strongly that this interglacial period was universal.

The evidence just given from glaciated regions is interestingly corroborated by climatic changes in unglaciated regions. Doctor Gilbert's well known proof of two moist periods in the history of lake Bonneville in Utah, with a dry interpluvial time, corresponding to two ice ages and an interglacial period, may be cited as an example of this, and also the parallel case of lake Lahontan. Dr Hans Meyer brings out the same facts in the Andes below glacial levels, where he finds terraces corresponding to two pluvial, = glacial, periods.[51]

Reference may be made also to Mr Huntington's notable paper on "Some characteristics of the glacial period in non-glaciated regions," wherein he correlates the alternating times of moister and drier climates in the Central Asian region with the advance and retreat of the glaciers in the Asiatic mountains. He believes there is no reasonable doubt that Central Asian moraines are synchronous with those of Europe.[52] In the Kalihari desert of South Africa Doctor Passarge, too, has found evidence of an alternation of moist and dry climates and refers to certain sand dunes as formed in interpluvial times, the equivalent of interglacial periods.

It will be seen, then, that climatic changes which have taken place in non-glaciated regions strongly support the evidence for interglacial periods in glaciated regions. When two different lines of research lead up to the same conclusion the probability of the correctness of that conclusion is, of course, very much strengthened; so that we may safely assume that interglacial periods were worldwide in Pleistocene times.

Interglacial Periods in Ancient Ice Ages

The best known of the ancient glacial periods, that of the Permo-Carboniferous, has been sufficiently studied in some regions to make it worth while to look for evidence of interglacial times, and the literature

[51] In den Hoch Anden von Equador.
[52] Bulletin of the Geological Society of America, vol. 18, pp. 351-388.

has been scanned with this in view. In India most references to the Talchir and Salt range are brief and not detailed, so that little information as to interglacial beds is to be expected. The published sections also give little evidence in favor of a removal and readvance of the ice-sheets; but Mr Lydekker mentions the fact that there are several boulder beds at different horizons,[53] and it may be that observers have not recognized the importance of noting stratified beds between the sheets of boulder clay.

In Australia Professor David has given an extraordinary section from the Bacchus Marsh district in Victoria, in which there are no less than a dozen beds of "glacial mud stones," separated by stratified materials, chiefly sandstone and conglomerate, the whole series being 2,000 feet thick. In New South Wales also a group of Coal measures, over 230 feet thick and comprising from 20 to 40 feet in thickness of coal (the Greta Coal measures), is sandwiched in between the erratic-bearing horizon of the Lower Marine series and the similar horizon of the Upper Marine series.[54]

In South Africa the southern Dwyka is often very thick, 1,000 or 1,300 feet, and includes much interstratified shale or sandstone or conglomerate, clearly of an interglacial nature; but little attention has been paid to this feature, and, so far as I am aware, no attempt has been made to follow up these interglacial deposits so as to indicate the extent of the retreat of the ice-sheet. Doctor Molengraaff mentions the stratified deposits between the sheets of tillite and suggests that there was a periodical forward and backward movement of the ice, but evidently looks on these movements as of small extent at the borders of the ice-sheet.[55] Mr Rogers describes a conglomerate pavement in which a second advance of the ice has smoothed and scratched the blocks in a lower tillite 50 to 80 feet thick, and states that there is some stratified shale without pebbles interbedded with the conglomerate.[56]

From my own observations it may be stated that stratified materials occur within the Dwyka at several places in South Africa, sometimes in beds of considerable thickness. Important beds of sandstone occur in Cape Colony near Matjesfontein, and near Laingsburg also the section of Dwyka, standing nearly vertical, shows at the bottom a thick layer with many boulders, followed by 150 or 200 feet of shale, well stratified and with no large stones, and then another thick bed of unstratified tillite.

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[53] Journal of the Geological Society of London, vol. xlii, p. 261.
[54] Ibid., vol. lii, 1896, p. 300.
[55] Geology of the Transvaal, p. 71.
[56] Geology of Cape Colony, pp. 162-164.

Some irregular masses of sandy conglomerate occur in the boulder clay also.

Near Vereeniging, in Transvaal, there is an apparently interglacial bed of sandstone including a small seam of coal with a thick bed of boulder clay beneath and a thin sheet of conglomerate above, but there is some doubt as to the glacial nature of the upper conglomerate. It may be water formed, recomposed of stones from the tillite beneath.

At N'gotsche mountain, in northeastern Natal, the Dwyka is 480 feet thick and includes in the upper part two thin beds of shale, and still higher a quite thick interglacial sandstone, above which is a fairly thick bed of sandy tillite with many boulders.

The succession of boulder clays and stratified shale and sandstone or conglomerate seen at some points in South Africa matches well the section of boulder clay and interbedded clay and sand of the Pleistocene interglacial section at Scarboro, near Toronto, and probably represents a similar series of events, though no fossils were observed in the African deposits to give indications of changes of climate. That there are interglacial beds of great thickness, implying a considerable lapse of time, in the Dwyka can be stated with certainty; but how completely the ice was removed in these interglacial periods is doubtful, because of the small amount of evidence available.

There were at least local interglacial stages in all three continents during the Permo-Carboniferous ice age, but whether these interglacial stages covered the whole of each area or coincided in the different continents must remain problematic.

As to the early Cambrian ice age there seems little evidence at hand either in favor of or against interglacial periods, except in Australia, where fossiliferous limestone is reported from between layers of tillite by Professor David.

The Lower Huronian boulder conglomerate, about 500 feet thick, at Cobalt has stratified slaty beds between unstratified beds of graywacke with angular and subangular boulders. Above the Lower Huronian comes a Middle Huronian conglomerate, sometimes boulder-bearing, which may represent a recurrence of glacial conditions, but no striated stones are known from it, perhaps because they have not been looked for.

In general it may be stated that interglacial stratified deposits free from boulders, indicating at least local changes of climate, are known from all of the glacial periods; but these have not been followed up sufficiently to judge of their universality in the older periods. In the Pleistocene ice age of North America there is proof of at least one complete

removal of the ice with a warmer climate than at present, followed by the formation of another great ice-sheet. Similar changes occurred in the Alps and Russia, and, as many geologists believe, in northwestern Europe also; and two widely separated ice-advances are reported from Patagonia, the Andes, and mount Kosciusko in Australia. It is probable that at least one interglacial period was worldwide.

Conclusions

From the previous discussion certain conclusions may be drawn:

1. Glacial periods occur at wide intervals almost to the beginning of known geological time and are a normal feature of the earth's history.

2. Glacial deposits were so widely spread in at least three of the periods that the temperate and polar regions of both hemispheres were affected, and in one of them the tropics also were invaded by land ice which reached sealevel on three continents.

3. There is a remarkable focussing of great ice-sheets about certain centers in two of the glacial periods, the north Atlantic in the Pleistocene and the Indian ocean in the Permo-Carboniferous.

4. At least one interglacial period was probably worldwide in the Pleistocene, and important interglacial beds occur in the older boulder clay deposits also. It is necessary, then, to account for very long periods of mild climate undergoing only slow change, separated by comparatively short periods of rapidly alternating cold and warm climate.

If the foregoing conclusions from glacial geology are admitted, various theoretical consequences ensue. If ice ages go back almost to the earliest known times, we must give up the idea of a formerly molten earth slowly cooling from age to age, unless the cooling ran its course before the earliest geological formations were deposited. The nebular theory, as usually understood, must be relegated to a past so distant as to have little interest for the geologist, or must be thrown overboard altogether.

With the nebular theory goes also Sir George Darwin's ingenious theory of the origin of the moon by tidal action, unless that, too, be pushed many millions of years farther back than his calculations indicate. The cross-bedded sands and the boulder clays, now changed into hard rocks in the Huronian, hint of no greater heat and of no stronger tidal action then than now. There was no commotion such as must have been raised in the seas of an earth rotating at four times its present rate beneath a moon one-half as far away as at present.

The departure of the molten earth, with its supposedly thin and easily bent or broken crust, sweeps away with it many of the usual theories of

ancient mountain building and eruptive activity, and also the usual conception of the original of the schistose rocks of the "basal complex."

We can no longer account for the supposed uniformity of past climates from the equator to the poles by assuming a supply of heat from beneath. Instead we must adjust our theories to an earth cold on the surface from the beginning, perhaps even warming up by internal work and the action of radiant matter, but more probably undergoing comparatively little change in temperature.

Certain other climatic theories are ruled out also. No merely local cause or probable combination of local causes, such as those skillfully suggested by Professor Gregory,[57] seems capable of covering the ground in a great ice age like that of the Pleistocene or the Permo-Carboniferous. Local elevations of thousands of feet can hardly be conceived as taking place at the same time over most of North America, the whole length of the Andes and Patagonia, all northern Europe, the Alps, the mountains of Turkestan, the Himalayas and Altai mountains, the Atlas region, Ruwenzori, Kenia and Kilimanjaro, the New Zealand Alps, and Kosciusko in Australia, not to mention other localities glaciated in Pleistocene times. The theory breaks down of its own weight. It should be added, however, that elevation in some cases is hostile to the formation of ice-sheets, as Scott has shown on the Antarctic tableland 9,000 feet above the sea, where the ice is dwindling and the glaciers are retreating.[58] There depression might extend glaciation by increasing precipitation.

Again, the mere enumeration of points where glaciation took place in the Pleistocene—some on broad low plains, others on mountains, some on isolated islands or the seacoast, others, like Ruwenzori and the Keewatin ice-sheet, in the heart of a continent—seems enough to discredit theories in which an adjustment of "highs" and "lows," of winds and precipitation, is brought forward to account for ice ages. Could any imaginable shifting of barometric pressures produce the enormous Permo-Carboniferous ice-sheets of India, Australia, and South Africa, all touching the tropics on plains reaching to sealevel?

Some general cause, applicable to the whole world, must be assumed, such as a change in the sun's heat or in the composition of the atmosphere, to account for periods of universal refrigeration, separated by long periods of mild climate reaching even to the polar regions. But the cause must permit also of comparatively rapid oscillations to account for warm interglacial episodes. The astronomical theories founded on the

[57] Climatic variations. Mexican Geological Congress, 1906.
[58] Voyage of the *Discovery*.

varying eccentricity of the earth's orbit seem to be ruled out, as shown by more than one writer, because of the relatively large number of rather evenly distributed ice ages which they suggest, and also by the assumption of alternating conditions in the two hemispheres. All the geological evidence points toward simultaneous glaciation in the northern and southern hemispheres, and the great extension of glaciers on mountains under the equator is inexplicable on the theory of varying eccentricities of the earth's orbit.

On the other hand, the strange clustering of great ice-sheets about certain centers suggests some factor which is not universal, but local in a broad way. A shifting of the poles of the earth has naturally been brought forward to account for the Permo-Carboniferous ice-sheets on low ground on both sides of the tropics; and this would aid in solving some of the problems connected with such an ice age, but would raise new difficulties in other directions.

If we imagine the south pole of the earth shifted to the central point between the glaciated areas in South Africa, India, and Australia, it would stand about in latitude 20° or 25° and longitude 75° as compared with the present arrangement. The distance of the nearest glaciated regions on the three continents from the supposed pole would be about 35°, so that their latitude would be 55° south. Under present conditions this would not imply glaciation unless on ground rising much above the sealevel. The glaciated points farthest away from the pole, as, for example, in New South Wales, would have a latitude of about 24° south of the new equator, which would make ice action impossible except on very high mountains, with a zonal arrangement of climate like that at present.

The effects on the climate due to the much greater inclination of the earth's axis to the ecliptic are, however, not taken into account here. No doubt the much greater difference between summer and winter and the relative narrowness of the tropical belt would greatly affect climates, but it would lead too far to discuss the results here.

If the south pole stood in the middle of the Indian ocean or of a Gondwana land occupying its present position, the north pole would be in northern Mexico, near the boundary of New Mexico or Texas. Glacial conglomerates have not yet been reported from the Permo-Carboniferous of that region, though a conglomerate suggesting ice action has been described by Doctor Cross from Colorado; and it is improbable that such tremendous glaciation could exist in the southern hemisphere, while regions much nearer the north pole were not greatly refrigerated.

A shifting of the poles would do little toward accounting for the Permo-

Carboniferous ice age, and would, of course, be quite inapplicable to the Pleistocene period, so that it may be left out of account.

The most probable general cause for ice ages is to be found in changes of the composition of the earth's atmosphere, as suggested long since by Professor Tindall and more recently by Professor Arrhenius and elaborated by Professor Chamberlin, since known, or possible results of the increase or decrease of carbon dioxide and of aqueous vapor would go far to produce the necessary changes of climate. It is highly probable, however, that to the general atmospheric causes should be added important local changes, as, for example, of level, of ocean currents through rising or sinking of sea-bottoms and land surfaces, or of the shifting of centers of high and low pressure.

It may be that ice ages can only be produced by a combination of causes, local and general, and that an eclectic grouping of theories will ultimately prove most satisfactory.

Whatever theory of ancient climates is adopted must provide for long periods of fairly uniform mild climates over the whole earth except on lofty mountains, and for relatively brief periods of oscillation between cold and warm climates during the so-called ice ages. Mr Huntington's diagram of cycle climatic changes illustrates this idea very well,[59] though the times of rapid oscillation should probably be separated by much longer stretches of comparative uniformity than he has indicated.

Since this paper was made ready for publication the Compte Rendu of the Mexican Geological Congress has reached me, containing a number of important papers on related subjects by Professor David, Professor Frech, Professor Gregory, Mr Manson, and others, which should be consulted by any one interested in glacial geology. Mr Manson's ingenious theory of changes of climates as due to the cooling of the earth, followed by the clearing away of clouds and the beginning of solar control of temperatures on the earth, is of course completely at variance with the evidence given above, showing that extensive ice-sheets reached sealevel in ancient times. Professor Frech's argument against interglacial periods from the distribution of extinct mammals seems too vague to counterpoise the direct evidence in favor of at least one interglacial period shown in so many different parts of the world.

The papers by Professor David strongly support several of the points brought forward in the preceding pages and form an important addition

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[59] Bulletin of the Geological Society of America, vol. 18, p. 362.

to our knowledge of ancient glacial periods. His discussion of the causes of ice ages also is suggestive and worthy of note.

The series of papers as a whole shows how lively an interest is now being taken in ancient climatology, and also how divergent the views are of the various geologists who are attacking the subject.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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STRATA CONTAINING THE JURASSIC FLORA OF OREGON[1]

BY J. S. DILLER

(Read before the Society December 31, 1907)

CONTENTS

[1] Published by permission of the Director of the United States Geological Survey.
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Introduction

Problem and Conclusion

Two fossil floras have been reported from the Mesozoic rocks of California and Oregon, the one Cretaceous and the other Jurassic. With the former the fauna is Cretaceous, but with the latter the fauna has been regarded as a matter of doubt. It is the purpose of this paper to remove the doubt by showing that in part of Oregon and California the Jurassic flora, as illustrated in the accompanying diagram, is in the "Myrtle" and Knoxville beds, while elsewhere it extends down to the horizon of the Mariposa, and the general conclusion is reached that for the Pacific coast the line between the Cretaceous and the Jurassic is the great unconformity at the base of the Knoxville.

	Oregon.		*California.*		
	Umpqua		Tejon		Eocene.
	Chico		Chico		Upper Cretaceous.
	"Myrtle."	Shasta flora.	Horsetown.	Shasta.	
Aucella crassicollis					Lower Cretaceous.
Aucella piochi	"Myrtle."	Jurassic flora.	Knoxville.		
	Dothan.		Franciscan.		
Aucella erringtoni	— —	Correlation not fully established	(?)		Jurassic.
	Galice.		Mariposa (regarded=Monte de Oro.)		
	Paleozoic.		Paleozoic.		

HISTORICAL DEVELOPMENT

The discovery of fossil plants by Aurelius Todd in Douglas county, Oregon, more than thirty years ago has led finally, through the collections of Will Q. Brown and the much larger collections of the U. S. Geological Survey, to an extensive study of the fossil flora of that region. Professors Lester F. Ward and William M. Fontaine have been the chief investigators, and their results appear in the Twentieth Annual Report (part ii, pages 368-377) and Monograph XLVIII of the U. S. Geological Survey. They regard the flora as Jurassic and studied it from three localities in Oregon: one in the neighborhood of Buck mountain, extending north across Thompson branch of Olalla creek in Douglas county; another in the same county, near Nichols station, on Cow creek; and a third, the most important, on the forks of Elk river, in Curry county, beside a very important locality near Oroville, California, at the western foot of the Sierra Nevada.

Since the investigations of Ward and Fontaine were published my field party of the Geological Survey has mapped and somewhat extended the localities in Oregon and discovered a number of new localities of plant beds containing the same flora in the Klamath mountains of Trinity county, California, especially at Big Bar and Rattlesnake creek.

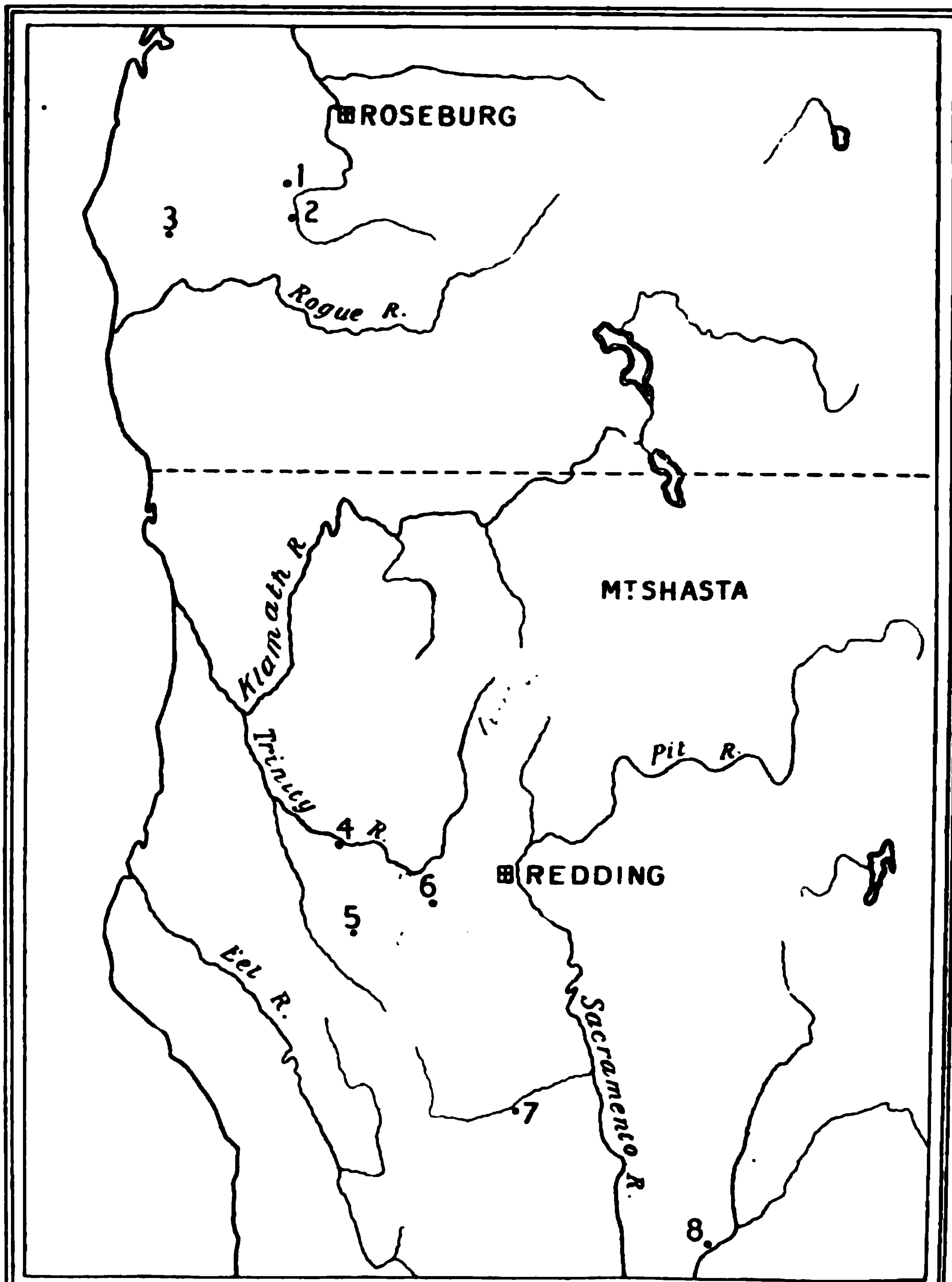

Figure 1.—*Map of Part of Oregon and California*

Showing localities of plant beds containing the "Jurassic flora of Oregon" and the "Flora of the Shasta" series

1. Buck Peak and Thompson creek, Oregon. "Jurassic flora of Oregon."
2. Near Nichols station, Oregon. "Jurassic flora of Oregon."
3. Elk river, Oregon. "Jurassic flora of Oregon."
4. Big Bar, California. "Jurassic flora of Oregon."
5. Rattlesnake creek, California. "Jurassic flora of Oregon."
6. Redding creek, California. Flora of Shasta series (Horsetown).
7. Near Wilcox's, west side Sacramento valley. Flora of Shasta series (Knoxville).
8. Near Oroville, California. "Jurassic flora of Oregon."

The Mesozoic plant localities considered in this paper are shown in figure 1.

Plant Beds of Buck Peak and Thompson Creek, Oregon

COMPOSITION AND ATTITUDE

The plant beds of the Buck Peak region are best exposed along Thompson creek, where, as shown on the accompanying sketch map, figure 2[a], they form a belt a mile in width. They are composed very largely of conglomerate, with a small proportion of sandstone and shale at the top, where fossil plants are most abundant. The general dip is to the westward at an angle of about 38 degrees, and a great thickness of strata, possibly more than 1,000 feet, is well displayed. At least three-fourths of the whole mass, its lower—that is, older—portion, lying upon the eastern side, is conglomerate, and it is composed for the most part of greenstone pebbles apparently derived from the mass which limits the conglomerate on the east. This is especially true of the basal portion. In the middle and upper portions of the conglomerate pebbles of chert, sandstone, and conglomerate become more abundant and finally predominate, making a conglomerate like much of that in the "Myrtle formation." Small beds of sandstone and shale occur locally throughout the basal conglomerate, and some of them contain distinct traces of leaves, showing that the greater part and possibly the whole thickness of the conglomerate belongs to the plant beds.

The first leaves were found in this section, in a thin bed of shale within massive sandstone, a short distance below the dam, but the principal leaf locality is 75 feet higher in the succession, in the basal portion of the sandstone and shaly sandstone which forms the upper 180 feet of the exposed section and passes unconformably beneath the Eocene. In this section the youngest of the plant beds is covered by the Eocene.

LITHIFICATION AND VEINING

The sandstones and conglomerates of the plant beds are not so firmly lithified as to break with a smooth fracture surface through the grains or pebbles, and in this respect are more nearly like the average of the Knoxville beds than of the Dothan. None of the beds were found with evident siliceous cement, although a few small but distinct veins were observed.

[a] This map, prepared originally from Land Office plats and modified by criticisms in the field, still has many inaccuracies, but is the best means yet available for showing the areal distribution of the various formations.

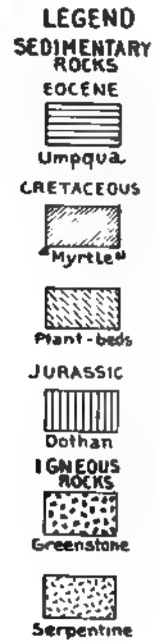

FIGURE 2.—*Nichols and Buck Peak Region, Douglas County, Oregon*

Dr F. E. Wright kindly examined the vein material for me, and found it composed chiefly of laumontite with a small amount of quartz.

FOSSILS OF THE PLANT BEDS

On Thompson creek and the eastern slope of Buck peak, a complete collection of plants was made at various times by Will Q. Brown, Professor Lester F. Ward, James Storrs, and the writer, and the flora has been thoroughly worked up and published by Professors Ward and Fontaine in the reports of the U. S. Geological Survey. The flora as described consists of about 77 species, listed in Monograph XLVIII, page 140, and no other forms have since been discovered in the original localities. Their conclusion with reference to geologic age is that, "so far as they throw any light on the question of age, they indicate that it is Jurassic."

Shells are of exceptional occurrence in the leaf beds. Though carefully sought for, they have rarely been found, but on account of their bearing on the age of the deposit all the evidence should be recorded. A doubtful fragment found with the plant fossils on Thompson creek was referred to Doctor Stanton, who reports that "the fragment seems to be part of a shell and is probably an Aucella, though there is not enough of it for positive identification."

RELATION TO THE "MYRTLE FORMATION" OF BUCK PEAK

The summit of Buck peak is conglomerate and sandstone containing the characteristic "Myrtle" (Knoxville) forms, *Aucella piochi* and *A. crassicollis*. Twelve hundred feet below the summit, on the northeastern slope, at the "Todd locality," the plant beds shown in figure 3 occur, dipping westward conformably, beneath a conglomerate containing many indefinite vegetable fragments as well as good specimens of *Aucella piochi*. These plant-bearing beds surely belong to the "Myrtle."

In the upper 200 feet of plant beds exposed at that place there are half a dozen beds of fine conglomerate, ranging from 2 to 10 feet in thickness, like the immediately overlying aucella-bearing conglomerate, suggesting continuous sedimentation, and that the plant beds belong to the "Myrtle formation."

Recognizing this probability, at Buck peak we have taken every opportunity afforded in the region to examine the basal beds of the "Myrtle" for plants, and traces of plants have been found at a number of localities, but at only one place have we found a determinable species. Three miles northeast of Riddles, in a gap of the ridge in southeast quarter of section 8, with good specimens of *Aucella piochi*, a fossil plant was found

which Doctor Knowlton identified as *Tæniopteris oregonensis* ? Font., and remarks:

"Minute fragments of one species only, which seems to be the species above given. Its age would seem to be the same as the so-called Oregon Jurassic; at least there are not enough data available to decide otherwise."

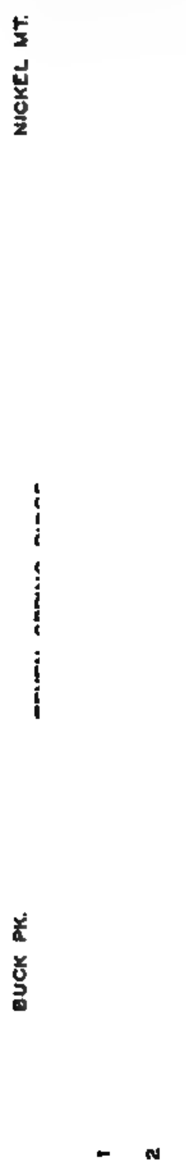

FIGURE 3.—*Section from Buck Peak east 4 Miles to Nickel Mountain*

1, Eocene, Umpqua formation; 2, Cretaceous, "Myrtle formation; 3, Cretaceous, "Myrtle" plant beds; 4, Greenstone; 5, Serpentine; 6, Jurassic, Dothan formation.

As this species occurs at several places in the plant beds on Thompson creek and at the Todd locality on the slope of Buck peak, its occurrence in the Riddles region in the same bed with *Aucella piochi* is of much importance as confirming the tendency of the evidence already cited to show that the plant beds belong to the "Myrtle formation."

RELATION TO THE DOTHAN FORMATION

The basal conglomerate of the plant beds on Thompson creek and Seven Spring ridge, as shown in figure 3, rests on the greenstone, from which many of its pebbles appear to have been derived. The conglomerate thins rapidly to the southwest, but continues across the West fork of Doe creek and Buck creek to the point where it disappears beneath the great mass of Eocene. Before disappearing it passes from the greenstone to the Dothan, with which the plant beds are in contrast. The Dothan is much altered and veined with quartz, and its dip is 60 degrees to the southeast. On the other hand, the plant beds show scarcely a trace of silicification, and dip in the opposite direction. The contact was not seen, but the contrast both in character and position of the two sets of strata indicates a decided unconformity.

This view is corroborated by their relation to the adjacent greenstone, which on the one hand intrudes the Dothan and on the other furnished sediment for the plant beds.

The interval between the two epochs of sedimentation, the Dothan and plant beds, was

one of decided deformation and silicification as well as of igneous intrusion.

Plant Beds near Nichols Station, Oregon

COMPOSITION AND ATTITUDE

On Cow creek, by the Southern Pacific railroad, near the whistling post, half a mile north of Nichols station, as shown on the map (figure 2), several small but important outcrops of the plant beds occur. They are completely surrounded by the Eocene and have been laid bare by its erosion.

The plant beds are fine, dark, shaly sandstone or sandy shale, much squeezed and checked, but without alteration or quartz veining. There are some calcareous nodules and spheroidal weathering is frequent. Beds of fine conglomerate, 2 to 5 feet thick, are occasionally interbedded with the sandy shale, and the entire mass, about 200 feet in thickness, dips to the southeast at an angle of about 60 degrees. The easternmost locality lies on the north slope of a ridge, under a gap several hundred feet above Cow creek, and the beds are not well exposed, but they are of much importance on account of their fossils.

From the plant beds of the Nichols region 45 forms are described, many of which occur in the vicinity of Buck mountain. These two are the type localities of Ward and Fontaine and have thus far afforded a flora of 77 forms, referred to as the "Jurassic flora of Douglas county, Oregon."

RELATION TO ADJACENT ROCKS

The Eocene is chiefly coarse sandstone or conglomerate and has a smaller dip than the plant beds with which it is seen in unconformable contact at several points along the stream. The Eocene in the immediate vicinity is not fossiliferous, but fossils occur half a mile to the north and in the neighboring table mountain.

The relation of the plant beds to the "Myrtle formation" on the one hand and the Dothan on the other is not a matter of direct observation, for their contacts in the neighborhood of Nichols are concealed.

Mr Will Q. Brown, the discoverer of the Nichols area of the Mesozoic plant beds, reports finding in the ridge area east of Cow creek a fragment containing a typical specimen of *Aucella piochi*, with others containing Mesozoic plants. Plant beds cover the whole of this small area, and though it may not be stated positively that the Aucella came from the plant beds, yet, since all the surrounding rocks are Eocene, the plant beds seem to be the most probable source of the Aucella, and this occurrence,

as that of Buck peak, tends to bind the plant beds closely to the "Myrtle formation."

The fossiliferous Dothan sandstone and conglomerate occur in the ravine a quarter of a mile southwest of the whistling post locality of the plant beds, and the two are separated by a line of disturbance and silicification which crosses Cow creek near the serpentine, half a mile north of Nichols station. South of the serpentine, about Nichols and beyond, the Dothan strata are much disturbed. They have an aspect of somewhat greater age than those of the plant beds, due to the fact that the Dothan contains occasional bunches or veinlets of either or both calcite and quartz. The difference in the degree of lithification between the plant beds and the Dothan is not nearly as great in the Nichols region as along Thompson creek, where the two are separated by a mass of greenstone.

Plant Beds of Elk River, Oregon

Occurrence

In the Port Orford folio of the U. S. Geological Survey, page 2, attention is called to fragments of plant-bearing shale found scattered along the bed of Elk river for a mile or more, from the forks of the river down to the mouth of Blackberry creek. The shales containing the leaf fragments are dark, rather sandy, and veined with calcite, like most of those which outcrop along that portion of the stream. They are interstratified with frequent layers of calcareous material, beds of sandstone, and fine conglomerate, most of which are fossiliferous.

At the time the survey was made of the Elk River region for the Port Orford folio, comparatively little attention was given to the fossil plants. They were not found in place, so that the relation of the plant beds to the other fossiliferous strata was then unknown. As the importance of these beds was recognized, it became necessary to obtain further information. Mr James Storrs, who has been the special collector of fossils in my field party for a number of years, was sent in October, 1907, to the forks of Elk river to locate the plant beds, collect fossils, and determine the relations of the strata containing the plants and shells. His success will appear in the sequel.

The dip of the beds on Elk river below the forks is to the northwest, and the course of the main stream makes but a small angle with the strike, but the two forks make large angles with it—the North fork in the newer and the South fork in the older strata.

The total thickness of the strata in which fossil plants have been found on Elk river is apparently somewhat over 1,000 feet. These plant beds

are underlain on the South fork by a heavy mass of conglomerate containing in its lower part many large pebbles of the greenstone like that on which the conglomerate rests at the base of the "Myrtle." No plants were found in the basal conglomerate, though it contains many examples of *Aucella crassicollis.*

FOSSIL PLANTS

The fossil plants were found in place as well as in many loose pieces along the bed of Elk creek from near the mouth of Blackberry creek to the forks and up the North fork at least a mile and a half. On the South fork the plants have not been found farther than 200 yards above the forks. All the beds above that point lie beneath the plant beds.

The first collection of fossil plants from this locality was studied by Professor Fontaine, who identified the following species:

Dicksonia oregonensis Font.
Thyrsopteris murrayana (Brogniart) Heer ?
Cladophlebis vaccensis Ward.
Ctenis sulcicaulis (Phillips) Ward ?
Ctenophyllum ? n. sp. ?
Podozamites lanceolatus minor (Schenk) Heer ?
Otozamites oregonensis Font. n. sp.
Taxites zamoides (Leckenby) Seward.

The collection recently made by Mr Storrs was examined by Dr F. H. Knowlton, who identified the following forms:

Yuccites hettangensis ? sp.
Sagenopteris paucifolia (Phill.) Ward.
Sagenopteris göppertiana Zign.
Cladophlebis pecopteroides ? Font.
Dicksonia oregonensis Font.
Ctenophyllum angustifolium Font.
Nilsonia parvula (Heer) Font.
Nilsonia orientalis minor Font.
Nilsonia sp. ?
Tæniopteris ? *oregonensis* Brogn.
Hausmannia sp.
Podozamites lanceolatus latifolia (Br.) Heer.
Podozamites sp.

Both sets of fossils were collected along the same portions of the stream beds, and it is rather surprising that only one species, namely, *Dicksonia oregonensis* Font., occurs in both lists. It is to be noted, however, that this is the most common form. The flora contains 20 species, all of which, according to Doctor Knowlton, "with the exception of the un-

named species of Hausmannia, are found in the beds of Douglas county, Oregon, which have been stated by Fontaine and Ward to be of Jurassic age."

FOSSIL SHELLS

Throughout the plant beds numerous shells are found intermingled with the plants, so that there can be no question whatever as to their association and contemporaneity. The following list contains all the forms identified by Doctor Stanton from this locality:

Spondylus ? sp.
Aucella crassicollis Keyserling.
Inoceramus ovatus Stanton.
Turbo morganensis Stanton.
Olcostephanus mutabilis Stanton.
Perisphinctes ? sp.
Hoplites hyatti Stanton.
Belemnites tehamaensis Stanton ?
Belemnites impressus Gabb.
Pinna ?
Fish scales.
Vertebra of an undetermined marine reptile.

The fauna, as far as known, includes 10 distinct forms. Concerning this fauna Doctor Stanton says:

"The collection consists of a number of small lots containing very few species, the most abundant and persistent being *Aucella crassicollis* Keyserling, which past experience shows to be characteristic of the upper part of the Knoxville formation and is believed to be confined to the Lower Cretaceous. In several of the lots there are a few ammonites and other fossils that are also Knoxville forms."

The collections by Mr Storrs were so made as to preserve the association of the forms, and concerning this matter Doctor Knowlton remarks:

"That many of the plants were found in association with Aucella and other invertebrates is no longer open to question, but I am still unable to see anything in the plants which would lead me to change my opinion as to their Jurassic age, but, on the contrary, the present collection confirms it."

RELATION TO THE "MYRTLE FORMATION"

It is evident from what has already been stated that, at the forks of Elk river, in Curry county, the plant beds clearly belong to the "Myrtle formation" and lie for the most part above the basal conglomerate. At any rate, no determinable plant remains were found in the basal conglomerate on the South fork of Elk river. The presence of so many specimens

of Aucella in the basal conglomerate under the plant beds on Elk river suggests that such fossils may yet be found in the corresponding conglomerate on Thompson creek in Douglas county.

RELATION TO THE DOTHAN FORMATION

Dothan fossils (*Aucella erringtoni*) have been found in loose pieces 6 miles northeast of the Forks of Elk river, on Johnson creek near the mouth of Sucker creek. The black slates at the mouth of Sucker creek are like the fragments containing *Aucella erringtoni* and are believed to belong to the Dothan formation. Similar black slates, with associated sandstones and calcareous nodules, occur on the South fork of Elk river about 2 miles above the forks, but only indefinite shell fossils[8] have been found in them. These strata are separated from the basal conglomerate of the "Myrtle" by a mass of greenstone which appears to cut the slates on the one hand and furnish sediments for the conglomerate on the other. The relation therefore appears to be at this point essentially as on Thompson creek—the basal portion of the "Myrtle" including the plant beds is unconformable to the Dothan and separated from it by a belt of greenstones intermediate in age.

PLANT BEDS OF BIG BAR, CALIFORNIA

OCCURRENCE

On Trinity river, California, about 20 miles west of Weaverville, in the vicinity of Big Bar, sometimes referred to as Coxes Bar, occurs one of the most important outcrops of Jurassic flora-bearing strata yet discovered in the Klamath mountains. The area is a small one, scarcely 2 miles in length northeast and southwest and three-fourths of a mile in width. It is dissected by several small tributaries of Trinity river into two distinct masses, which afford excellent exposures in the terraces where the gravel has been removed by the hydraulic process in the Pattison and Wilshire mines. The whole succession of strata in this area is scarcely 200 feet in thickness and composed chiefly of gray shales and sandstones, with a small proportion of fine conglomerate. These rocks are generally so soft

[8] Only a trace of plant fossils has yet been found in the Dothan, the trace being a small plant fragment found on Catching creek about 6 miles southwest of Riddle, in dark gray slates of the Dothan formation. Doctor Knowlton says of it: "This is probably the upper part of a leaf of Pterophyllum, such, for example, as *P. æquale*, as figured in Ward's Jurassic flora of Oregon. The tips of the leaflets and the nervation are not preserved, and this determination is very much in doubt." The locality was carefully examined again without finding any fossils.

that they were at first regarded as Tertiary.[4] Near the base, however, especially in the Wilshire mine, there are hard nodules cemented by carbonate of lime and iron.

A 5-foot layer of fine conglomerate or breccia, locally at the bottom, is made up almost exclusively of angular fragments of the schistose siliceous rocks on which it rests with marked unconformity. Very near the bottom the shales are carbonaceous and pass into a thin bed of impure coal.

STRUCTURE

The structure of the area appears to be a short and shallow synclinal basin, one arm of which is exposed in the Pattison mine and the other in the Wilshire, with dips varying from 20 to 45 degrees. In both mines the coal bed is exposed near the bottom, dipping generally in opposite directions, and is conformably overlain by fossiliferous shales and sandstones. The continuity of the beds is interrupted by small local faults, whose effect is to increase the apparent thickness of the beds, and it is probable that the thickness of 200 feet stated above is an overestimate.

FOSSIL PLANTS

Fossil plants have been collected in the Pattison mine near the middle and the western edge of the upper terrace and at the eastern edge of the lower terrace. In the Wilshire mine (old part) they have been found best preserved in the hard portions above the coal.

Fossil plants are most abundant in the lower portion of the pre-Tertiary plant beds, but occur scattered irregularly throughout the strata, and all belong to the same flora. They were referred to Dr F. H. Knowlton, who reports the following forms:

Dicksonia oregonensis Font.
Onychiopsis sp. (fruit).
Onychiopsis psilotoides Ward.
Cladophlebis sphenopteroides Font.
Cladophlebis vaccensis Ward.
Cladophlebis denticulata ? Font.
Cladophlebis sp.
Scleropteris oregonensis ? Font.
Tæniopteris orovillensis Font.
Tæniopteris vittata Brongn.
Tæniopteris sp.

[4] There is some Tertiary near by. The fossil leaves found abundantly in the south or new part of the Wilshire mine Knowlton regards as Tertiary. They are well preserved in the fresh exposures of soft shales by the waste ditch of the gravel mined in 1907 near the Chinaman's cabin.

Nilsonia orientalis minor Font.
Sagenopteris paucifolia Ward.
Sagenopteris grandifolia Font.
Hausmannia cf. *H. forschammeri dentata* Möller.
Sphenolepidium oregonense Font.
Pagiophyllum falcatum ?
Taxites zamioides Sew.
Podozamites lanceolatus minor Heer.
Seed, probably cycadaceous.

Doctor Knowlton remarks that—

"These fossils prove beyond question that the beds containing them are similar in age to the Jurassic of Oregon, since all but three of the forms (*Onychiopsis* (fruit), *Hausmannia*, and *Pagrophyllum falcatum*) are common to the two areas."

FOSSIL SHELLS

Shells have been found in the same beds with the plants at both the Pattison and Wilshire mines, so there is no doubt whatever as to their association. The collections made at various times were referred to Doctor Stanton, who reports the following forms:

Pecten sp.
Mytilus sp.
Aucella crassicollis Keyserling.
Cyprina sp. ?
Unio sp.—undescribed species represented by several good casts.

Doctor Stanton states:

"The fossils from Big Bar, California, area are certainly upper Knoxville and hence Lower Cretaceous, as shown by the presence of typical specimens of *Aucella crassicollis*. The other invertebrate fossils from the same area are closely associated stratigraphically with the Aucella, but as they are either undescribed or unidentifiable species, they do not throw any additional light on the question of the age of the beds. Two of the lots consist entirely of an interesting new species of Unio, which is important as showing that part of the beds at Big Bar were deposited in fresh water."

As to the relation between the Aucella and Unio: The *Aucella crassicollis*, as far as yet observed, is limited to a bed of coarse sandstone 4 feet in thickness and has been found only on the western side of the area, on the upper bench of Pattison mine, interstratified with the plant beds, about 6 feet above their base. The Unio occurs most abundantly in a thin layer of clayey shale immediately below the Aucella bed. It occurs also in shales 50 feet above the Aucella bed and indicates the alternation

of salt and brackish or fresh-water conditions, possibly due to shifting sediments, or slight oscillation of the coast.

RELATION TO ADJACENT ROCKS

In both the Wilshire and Pattison mine the contact of the plant beds with the underlying Paleozoic rocks is well exposed and their unconformity is conspicuous; as may be inferred from the fact that the plant beds in general strike northeast and southwest with gentle dip and rest upon rocks whose strike is approximately at right angles and dip vertical. The basal conglomerate of the plant beds, as already noted, is made up largely of fragments derived from the adjacent somewhat schistose rocks and vein quartz whose alteration and silicification antedated the deposition of the plant beds.

The age of the underlying beds is certainly in part Carboniferous, for the limestone of that region is well characterized by fossils. The unconformity at the base of the plant beds represents a long interval, whose records occur in the Galice, Dothan, and perhaps other formations of Oregon.

Plant Beds of Rattlesnake Creek, California

OCCURRENCE

In Trinity county, California, 25 miles south of Big Bar, there is another small area of plant beds. It occurs in the drainage of Rattlesnake creek, 7½ miles southwest of Peanut, by the trail to the old Scott place, on the South fork of Trinity river. The strata are sandstones, shales, and conglomerates, which strike north 15 degrees east and dip 30 degrees northwest.

Mr Storrs reports many shells and plants in the same strata, and their association is well illustrated in the specimens collected.

Doctor Knowlton reports as follows concerning the plants:

FOSSILS

"*Cyclopitys oregonensis* Font.
Tæniopteris vittata Brongn.
Sequoia reichenbachi (Gein.) Heer.

"The specimen of Cyclopitys mentioned above is a fairly good one and can not possibly be mistaken for anything else; but the species of Tæniopteris is based on only a small scrap, though it agrees well, so far as can be made out, with the species given. *Sequoia reichenbachi* is a species of wide distribution, and consequently of little value in fixing the age. It has not, I believe, before been reported in the Jurassic beds of California and Oregon, but was identified

by Fontaine in the Shasta beds. I regard this locality as being referable to the Jurassic."

Doctor Stanton examined the fossils and reports that "among the fossil plants are two small shells which appear to be young specimens of Unio, though they may belong to some marine genus instead."

RELATION TO OTHER FORMATIONS

This small mass of sediments, like that at Big Bar, rests with a marked unconformity directly on the upturned edges of the older rocks. The fossil flora is closely related to that of Big Bar, for two of the forms found here, namely, *Cyclopitys oregonensis* and *Tœniopteris vittata,* occur in the plant beds of Thompson creek and Buck creek, Oregon—type localities for the Jurassic flora of Oregon to which that of Big Bar belongs. The other form, *Sequoia reichenbachi,* occurs in the Horsetown beds of Rèdding creek, about 20 miles northeast of Rattlesnake, and it seems probable that the Rattlesnake Creek mass belongs to the top of the Knoxville or bottom of the Horsetown.[5]

Plant Beds of Redding Creek, California

It may be well in this connection to note that near Clements house, along Redding creek, in Trinity county, Storrs collected a number of plants, among which Knowlton recognized the following:

"*Sagenopteris oregonensis* Font.
Sagenopteris elliptica ? Font.
Gleichenia ? *Gilbert thompsoni* Font.
Cladophlebis heterophylla Font.
Sequoia reichenbachi (Gein.) Heer."

Knowlton remarks that—

"These species, with the exception of *Cladophlebis heterophylla*, which is known from the lower Potomac and Kootenai, are all reported by Fontaine from the Shasta flora of the localities along the west side of the Sacramento valley, and are therefore regarded as of Lower Cretaceous age."

The plants are commingled with marine shells which Stanton determined as *Pecten operculiformis, Trigonia leana, Cardium, ? Corbula,* and *Pleuromya papyracea,* and regards as lower Horsetown. At this locality

[5] On lithologic and stratigraphic evidence, Hershey regards it as Horsetown. American Journal of Science, vol. xiv, 1902, p. 34.

the Horsetown rests unconformably upon the Paleozoic rocks and Knoxville is absent.

Plant Beds of western Side of Sacramento Valley, California

FLORA

One-third of a mile west of Wilcox's house, 4 miles south of Lowry, in Tehama county, Storrs collected, in October last, a few specimens, among which Knowlton recognized—

> "*Nilsonia parvula* (Heer) Font.
> *Tæniopteris vittata* Brongn.
> *Cladophlebis* sp. ?
> *Sagenopteris* sp ?

"The material from this locality is all very fragmentary and the identifications of the two species given above are based on very small pieces that are really too minute to be so used, but to the best of my knowledge and belief they are correctly referred. This being the case, this locality is regarded as being Jurassic."

The occurrence of the "Jurassic flora of Oregon" with a Knoxville fauna at Elk river and Big Bar led to the expectation of finding it in the Knoxville beds near the base of the Coast range, along the western side of the Sacramento valley, in California.

In collections made from the Knoxville beds in that region in the fall of 1907 by Mr Storrs, Doctor Knowlton determined with doubt, as noted above, several forms as belonging to the "Jurassic flora of Oregon," but later collections from the same place removed all doubts. All the forms yet found in that region belong to the Lower Cretaceous (Shasta) flora of Ward and Fontaine. The collections were examined by Doctor Knowlton, who reports as follows:

"*Report on fossil Plants collected for J. S. Diller by James Storrs, February, 1908, on the western Side of the Sacramento Valley, Tehama County, California, by F. H. Knowlton.*

"No. 30. South fork of Cottonwood creek, 2 miles south of Stephenson's place and ¾ mile west of that point.

Cladophlebis falcata Font.
Cladophlebis parva ? Font.
Sagenopteris oregonensis (Font.) Font.
Sagenopteris elliptica ? Font.
Angiopteridium strictinerve Font.
Nageiopsis longifolia ? Font.
Zamites tenuinervis Font.

Cycadeospermum ? sp. new.
Equisetum texense ? Font.
Dicotyledon fragment of leaf.
All Shasta species.

"No. 32. South fork of Cottonwood creek, 2 miles south and 1½ miles west of Stephenson's place.
Cladophlebis parva ? Font.
Nilsonia. Fragment, not really determinable.
Nilsonia. A larger species than the last, but as it is only a scrap it can not be identified.
Angiopteridium strictinerve ? Font. Minute piece.
Shasta species, but not well determined.

"No. 34. One-third mile west and half mile south of Wilcox's.
Cladophlebis parva Font.
Cladophlebis browniana (Dunk.) Sew.
Cladophlebis ungeri (Dunk.) Ward.
Cladophlebis heterophylla Font.
Cladophlebis falcata Font.
Sagenopteris nervosa Font.
Angiopteridium canmorense ? Dawson.
Angiopteridium strictinerve latifolium Font.
Ctenis or *nilsonia*, probably new.
Dioonites dunkerianus (Göpp.) Miq.
All Shasta species.

"No. 824. One-third mile west of Wilcox's ranch. (Same as no. 34.)
Cladophlebis browniana (Dunk.) Sew.
Sagenopteris elliptica ? Font.
Angiopteridium sp.
Nilsonia stantoni ? Font.
All Shasta forms.

"No. 37. Four miles south of Wilcox's on McCartey creek, 2 miles west of road from Lowrey's to Paskenta.
Cladophlebis falcata Font.
Angiopteridium canmorense Dawson.
Angiopteridium strictinerve Font.
Oleandra graminæfolia Knowlton.
Tæniopteris. Probably a new species; nearest to a Jurassic form, but not the same.
Ctenis. A mere fragment, most like *C. auriculata* Font., of the Jurassic, but too small to be positive.
Nilsonia schaumbergensis (Dunk.) Nath.
Nilsonia. Nearest Kootenai species, but probably new.
Dioonites buchianus ? (Ett.) Born.
Nageiopsis latifolia ? Font.
Sphenolepidium sternbergianum (Dunk.) Heer.
Sequoia reichenbachi (Gein.) Heer.
Shasta or Kootenai species.

"By combining the species from the several localities, we get the following list of forms: [In this list the locality number at which each occurs is followed by a mark of interrogation (?) when the determination is regarded as doubtful, and by a mark of exclamation (!) when the identification is positive.]

Cladophlebis browniana 24 ?, 34 !
Cladophlebis falcata 30 !, 34 !, 37 !
Cladophlebis heterophylla 34 !
Cladophlebis parva 30 ?, 32 !, 34 !
Cladophlebis ungeri 34 !
Sagenopteris elliptica 24 ?, 30, ?
Sagenopteris nervosa 34 !
Sagenopteris oregonensis 30 !
Angiopteridium canmorense 34 !, 37 !
Angiopteridium strictinerve 30 !, 32 !, 37 !
Angiopteridium strictinerve latifolium 34 !
Angiopteridium ? sp. 24 !
Oleandra graminæfolia 37 !
Ctenis sp. 37 !
Ctenis or *Nilsonia* 34 !
Tæniopteris sp. 37 !
Dioonites buchianus 37 ?
Dioonites dunkerianus 34 !
Nilsonia schaumbergensis 37 !
Nilsonia stantoni 24 ?
Nilsonia sp. ? 32 ?
Nilsonia sp. ? 32 ?
Nilsonia sp. 37 !
Nageiopsis longifolia 30 ?
Nageiopsis latifolia 37 ?
Zamites tenuinervis 30 !
Cycadeospermum sp. 30 !
Equisetum texense 30 ?
Sphenolepidium sternbergianum 37 !
Sequoia reichenbachi 37 !
Dicotyledon 30 !

"This combined list includes 31 forms, but on eliminating those not specifically named we have 22 species identified with more or less certainty from this collection, and of these some 15 are determined positively as occurring at one or more of the localities. Not a single one of these species, according to the monograph of Fontaine and Ward, has been found in the Jurassic of California or Oregon, or in the Jurassic elsewhere, but all occur in the Shasta or Kootenai. There are several of the forms not specifically named, as pointed out under the above lists, that appear to have their closest affinities with Jurassic species, but they are not identical, so far as the material in hand will permit a judgment. With the above facts in mind, therefore, I do not hesitate to refer the present collections to the Shasta."

In the above report it is evident that Doctor Knowlton, following Professors Ward and Fontaine, regards the "flora of the Shasta series" not only as distinct from the Jurassic flora of Oregon, but also as younger. The former is considered as Cretaceous and the latter Jurassic.

Of the 22 species determined by Doctor Knowlton in the collections from the west side of the Sacramento valley, 5 had been previously reported by Ward and Fontaine from the Knoxville only, 5 from the Horsetown only, 7 from both Knoxville and Horsetown, 2 from the Knoxville, Horsetown and Chico, and 3 from the Kootenai.

FAUNA

In the same strata, more or less closely associated with the fossil plants, a few fossil shells were found by Storrs. No attempt was made to get shells not found closely related to the fossil plants. Large and complete faunal collections were made in the same region and described by T. W. Stanton[6] years ago. In Storrs' collection Doctor Stanton reports the following forms from the plant beds, and states that the horizon to which they belong is the upper Knoxville, within the zone of *Aucella crassicollis:*

Aucella crassicollis Keyserling.
Lytoceras batesi Trask.
Hoplites crassiplicatus Stanton.
Pinna sp. Similar species of *Pinna* are known in both earlier and later formations.

Plant Beds of Oroville, California

HISTORICAL

A little more than 3 miles in a direct line north 30 degrees east of Oroville, on the southern slope of Monte de Oro, at 8, figure 1, Mr H. W. Turner in 1886 observed some clay slate containing traces of fossil leaves. Beds of conglomerate were noted with the slates and reported to be made up in part of pebbles of (porphyrites) altered andesites. The strata were designated the Monte de Oro formation and briefly described in the Seventeenth Annual Report of the U. S. Geological Survey, part i, page 548.[7]

Dr T. W. Stanton visited the locality in 1894 and collected some good plants of great interest. The following year Professor Ward and James Storrs made large collections which have since been studied and described

[6] Contributions to the Cretaceous paleontology of the Pacific coast: The fauna of the Knoxville beds. U. S. Geological Survey Bulletin no. 133, 1895.

[7] The Monte de Oro formation is briefly described in some of the Gold Belt folios, beginning with no. 31, Pyramid peak, p. 1.

by Professors Ward and Fontaine in the Twentieth Annual Report of the U. S. Geological Survey, part ii, and Monograph XLVIII.

The plants were obtained in slates mainly in the next ravine east of Morris ravine, a little west of south from the Banner mine, between the wagon road and the river.

The identity of 12 out of the 28 fossil plants found near Oroville with those of the plant beds already referred to at Buck peak and Nichols, in Oregon, led Ward and Fontaine to regard the beds at Oroville as belonging to essentially the same horizon as the Oregon beds—that is, to late Jurassic.

LITHOLOGY

The Monte de Oro beds are composed of slates, sandstones, and conglomerates in small layers, irregularly interbedded. The slates, generally somewhat shaly, are gray to black in color and form more than half of the whole mass. Exposed to the weather, they become light colored and appear to be but little altered, though locally sheared and containing a number of quartz veins generally parallel to the slaty cleavage. Beneath the surface the slates appear more altered. They are often black, decidedly slaty, and more frequently traversed by veins of quartz. The yellowish to dark gray sandstones, often shaly, pass into conglomerate, which generally contains, besides siliceous pebbles and dark fragments of shale, numerous greenish pebbles of altered igneous rocks of andesitic types.

AURIFEROUS QUARTZ VEINS

Several definite auriferous quartz veins of considerable size occur in this belt and have been worked in the Banner mine, which is said to have yielded some hundreds of thousands of dollars. In answer to my queries concerning the relation of the ore bodies to the slate belt and whether there may be two formations in the belt, Mr George H. Evans and Landis S. Scrutton, successively superintendents of the Banner mine, have kindly furnished me the following information:

"The ore bodies of the Banner mine were found in just such slate rocks as are now visible on the surface. The vein was a very persistent one in depth. At the 1,000-foot level, the greatest depth attained, the vein was beautifully formed with fine smooth walls and the same character of country rock as at the surface. Speaking generally, however, the values almost gave out below the 500-foot level.

"There are at least four conspicuous quartz veins outcropping in the narrow Banner slate belt, but unless one is well acquainted with the spot, it is hard to find them on account of the brush.

"There is only one formation in the said slate belt as far as we know; bunches or lenses of conglomerate and sandstone are occasionally met with down to the greatest depth attained."

There can be no question that the plant beds at Oroville contain important ore deposits, which may be correlated with those found elsewhere in the Gold belt along the western slope of the Sierra Nevada.

DISTRIBUTION

The known area occupied by the Monte de Oro beds is small, not over 2,000 feet in width, and about 2 miles in length, extending from the slope of Monte de Oro, the end of Table mountain almost directly south, to Feather river, where an excellent section is exposed. To the northward they pass beneath the lava cap and Neocene deposits of Table mountain; to the southward their extent beyond Feather river is unknown, but is not believed to be great—perhaps a mile—for on both sides the beds are limited by volcanic rocks which cover a large area east and southeast of Oroville.

STRUCTURE AND THICKNESS

The strike of the rocks in the vicinity of the Banner mine is north 20 to 55 degrees west, with a dip of not less than 54 degrees to the northeast. Some places the beds are vertical, but generally they dip from 62 to 70 degrees to the northeast. Along the river, which affords a continuous section across the belt, the beds strike north and south and dip 52 to 85 degrees to the east, giving an estimated thickness for the monoclinal mass of approximately 900 feet. The fact that the conglomerates and sandstones are mainly along the borders, with slates prevailing in the middle of the area, suggests that the mass may be an apprest synclinal. If so, the thickness exposed is about 450 feet.

RELATION TO ADJACENT VOLCANICS

The fragmental character of the adjacent igneous rocks upon both sides of the plant beds shows that they are tuffs and amygdaloids, and consequently of volcanic origin. The tuffs are rarely bedded, but their contact above and below the plant beds dips to the eastward approximately parallel to the stratification, so that the plant beds, as first shown by Mr Turner (Journal of Geology, volume iii, page 394), appear to be interstratified with the tuffs. This view is favored by the fact that the conglomerates of the plant beds contain many pebbles like those of the tuffs. Furthermore, there are in the same region, at a different horizon, other masses of fossiliferous tuffaceous sandstone interbedded with the regular tuffs. Mr Storrs recently discovered a small one on the north bank of Feather river, one-fourth of a mile west of the mouth of Morris ravine, and the fossil shells it contains are the same as those of the Ban-

ner Mine area. The bulk of the evidence supports the view that the deposition of the plant beds at Oroville occurred during a quiet interval in the time of volcanic activity, but it is not yet certain that they are not later and occupy a syncline folded into the underlying volcanics.

FOSSILS AND AGE

A full account of the flora in the Monte de Oro formation is given by Professors Ward and Fontaine in the Twentieth Annual Report of the U. S. Geological Survey, part ii. The flora contains 28 distinct forms, of which 14 are new. There are 12 forms that may be compared with previously known ones in fixing the age, and 7 of these are Jurassic. The conclusion reached by the paleobotanists is that "the comparison of the Oroville plants with known floras shows that most of the forms for which any relationship with known plants can be made out find their like in the Lias and Oolite, or, without distinguishing these, in the Jurassic."

The shells found in the Monte de Oro formation by Mr Storrs have been examined by Doctor Stanton, who states that—

"The fossils from the plant-bearing Mesozoic beds near Oroville, California, are especially interesting for the reason that this locality has not previously yielded any invertebrates. Unfortunately the collection does not contain anything specifically identifiable with fossils from any well-known horizon on the west coast. The most abundant form is an aviculoid shell that I doubtfully referred to Eumicrotis. With these there are specimens of Pinna, Trigonia, and Belemnites. The whole assemblage has a decided Jurassic aspect, and, in my opinion, the formation yielding them is older than the aucella-bearing Mariposa formation."

In September, 1907, I again visited the Oroville locality with Mr Storrs and made additional collections in the hope of finding something distinctive. These were referred to Doctor Stanton, who reports as follows:

"About a year ago, in reporting on another collection obtained by Mr Storrs from these beds, I expressed the opinion that they are Jurassic and older than the Mariposa beds. The fossils now under examination add several species to the previous list, although I am still unable to assign them to described species, and they do not therefore afford a good basis for correlation with well established horizons. Perhaps the most important addition is the form doubtfully referred to Aucella. It is represented by one fairly good valve and a fragment of another, which might belong to either *A. piochi* of the Knoxville or to *A. erringtoni* of the Mariposa, as far as can be determined from the features preserved. Unfortunately there is no right valve in the collection and the generic reference is not positive. If it is really an Aucella, the age of the beds is either Mariposa or Knoxville—more probably the former. The general

character of the other forms is suggestive of the older Jurassic faunas of the Taylorsville region, but it must be admitted that there is no definite evidence of this."

The following list, prepared by Doctor Stanton, contains all the shells yet discovered in the plant beds at Oroville:

Ostrea sp.
Pecten. Two or three species.
Aucella ? sp. Two imperfect specimens with the form of *A. piochi* or *A. erringtoni*.
Modiola sp.
Trigonia sp.
Cardium ? sp. The abundant species that in a previous report was thought to be an aviculoid shell, and doubtfully referred to Eumicrotis. The specimens in the present collection are somewhat better preserved, but the generic reference is still doubtful.
Belemnites sp. Several fragments.

Horizon of Aucella crassicollis

The stratigraphic relations of the beds containing *Aucella crassicollis* are more clearly and extensively exposed along the western side of the Sacramento valley than anywhere else in California and Oregon. Although that region has not yet been mapped in detail because there is no appropriate topographic base, it has been studied with care for its structure and fauna[8] and a number of sections have been measured.

The Cretaceous rocks (Shasta series and Chico) have a total thickness on Elder creek, in Tehama county, of about 30,000 feet, of which the lower 20,000 belongs to the Knoxville, overlain by 6,000 feet of Horsetown and 4,000 of Chico. The various forms of Aucella, excepting *Aucella erringtoni,* which occurs in the Mariposa, have been recognized in the Knoxville and are considered by Doctor Stanton as two distinct species—*Aucella piochi* and *Aucella crassicollis*. Although the two forms sometimes occur near together, in general the strata containing *Aucella piochi* lie beneath those in which *Aucella crassicollis* is most abundantly developed, and the zone of the latter is apparently limited to the upper 2,000 feet of Knoxville beds, where it is associated with other forms which are characteristic of the same horizon. Elsewhere in California and Oregon the *Aucella crassicollis* zone may vary greatly in thickness, but wherever it occurs in determinable order it forms the top of the Knoxville next in succession below the base of the Horsetown. This general

[8] The Shasta-Chico series, by J. S. Diller and T. W. Stanton, Bulletin of the Geological Society of America, vol. 5, pp. 435-467, and Contributions to the Cretaceous paleontology of the Pacific coast: The fauna of the Knoxville beds, U. S. Geological Survey Bulletin no. 133, by T. W. Stanton.

succession is well illustrated on Myrtle creek, Elk river, and Rogue river, in Oregon, and locally in the Klamath mountains, but most fully and satisfactorily along the western side of the Sacramento valley, in California.

While it is possible that *Aucella crassicollis* may occur much farther down in the series than 2,000 feet from the top of the Knoxville beds, it has not yet been shown to have such earlier distribution, and until such evidence appears we are constrained to regard the section of the western side of the Sacramento valley as the standard.

Local Silicification of the "Myrtle Formation"

"MYRTLE" GENERALLY UNALTERED

In the Gold belt of the Sierra Nevada of California the Paleozoic strata were deformed and metamorphosed to a considerable degree before the deposition of the Mesozoic, but the great epoch of mineralization appears to have taken place at the close of the Mariposa. This is strongly indicated by the general fact that the Mariposa slates are often highly altered and contain important ore bodies, while the nearest Knoxville strata are unaltered.

The greatest mass of Knoxville strata known lies along the western side of the Sacramento valley, in Tehama county, California, and although locally veined with calcite is not perceptibly metamorphosed. A similar mass, not so thick, but quite unaltered, lies in Cow Creek valley and along Myrtle creek, in Douglas county, Oregon.

EXCEPTION TO GENERAL RULE

The Myrtle Creek mass noted above is limited on the northwest by Dodson Mountain ridge, beyond which, in the Dillard region, an area of the Knoxville occurs that is an exception to the general rule, for its rocks are locally affected by a considerable degree of silicification. Attention has been recently called to the rocks of this area by Mr Louderback, who regards its silicified rocks bearing quartz veins in variable abundance as typical of the Franciscan of California. While not questioning the lithological comparisons which Doctor Louderback's familiarity with the Franciscan has enabled him to make, I have been especially interested in the age of the rocks and the relation of the fossils to the silicification.

CALCAREOUS CEMENT AND QUARTZ VEINS IN THE "MYRTLE"

The cement in the sandstones and conglomerates of the Dillard area varies greatly and often abruptly from place to place. Where fossil shells are abundant, the cement is calcareous; but where they are rare or absent, especially in the sandstones, the cement may be siliceous and the rocks

veined more or less abundantly with small stringers of quartz. The abundance of fossils and the calcareous cement derived from them has in a measure restricted the circulation of the siliceous solutions to the portions poor in fossils, where the quartz veins in consequence are most common. Rarely the shells are replaced by pyrite.

CALCAREOUS CEMENT AND QUARTZ VEINS IN THE DOTHAN

In the northwest portion of the Riddles quadrangle, a few miles from the end of the Dillard area, and separated from it by a mass of greenstone, the Thompson Creek body of Dothan rocks occurs and contains characteristic specimens of *Aucella erringtoni*. As in the Dillard area, wherever the fossils are abundant the cement and veins are calcareous, but elsewhere they are siliceous. The Dothan rocks on Thompson creek are in most places not silicified or permeated by quartz veinlets any more than the Knoxville rocks of the Dillard area. Generally, however, other portions of the Dothan, where not fossiliferous, are more firmly silicified and abundantly quartz-veined than the rocks of the Dillard area.

AGE OF THE ROCKS

That the rocks of the Dillard area are Knoxville is indicated by the wide distribution of characteristic fossils, especially *Aucella piochii* and *Aucella crassicollis*. As indicated in the accompanying figure, they have been found at many points throughout the area. A sketch of the Dillard area was published in the American Journal of Science for June, 1907, page 416, but since then, in completing the Riddles quadrangle, the number of fossiliferous localities has been greatly extended, especially in the southwest portion and along the river above Dillard (figure 4), where well preserved forms occur in calcareous pebbles or concretions of an interesting conglomerate.[a]

If these fossiliferous nodules are pebbles derived from an aucella-bearing limestone, they would furnish evidence of a limestone characterized by *Aucella crassicollis* older than the rocks of the Dillard area, for the conglomerate in question is well exposed by the river and evidently interstratified with the rocks in the immediate vicinity of Dillard. Similar conglomerate with fossiliferous limestone nodules occurs on the river at the mouth of Rice creek. The adjacent sandstones at both localities contain calcareous concretions, and it is believed that the fossiliferous nodules also may be concretionary and of the same age in general as the rocks of the Dillard area to which the fossils correspond.

The best examples perhaps of *Aucella crassicollis* found this year

[a] The total number of distinct localities at which Knoxville forms of Aucella have been found in the Dillard area is sixty-four.

(1907) in the quartz-veined rocks occur near the southwest corner of the area adjoining the igneous rocks one-third of a mile north of Josten's house, in section 14, township 29 south, range 7 west, of the Willamette meridian, and also in section 29, township 29 south, range 6 west, Willamette meridian, on the trail from the upper part of Rice creek over to Willis creek. At both localities undoubted examples of *A. crassicollis* were obtained in fine conglomerates cut by quartz veinlets and interbedded with crushed sandstones that are occasionally full of such veinlets.[10]

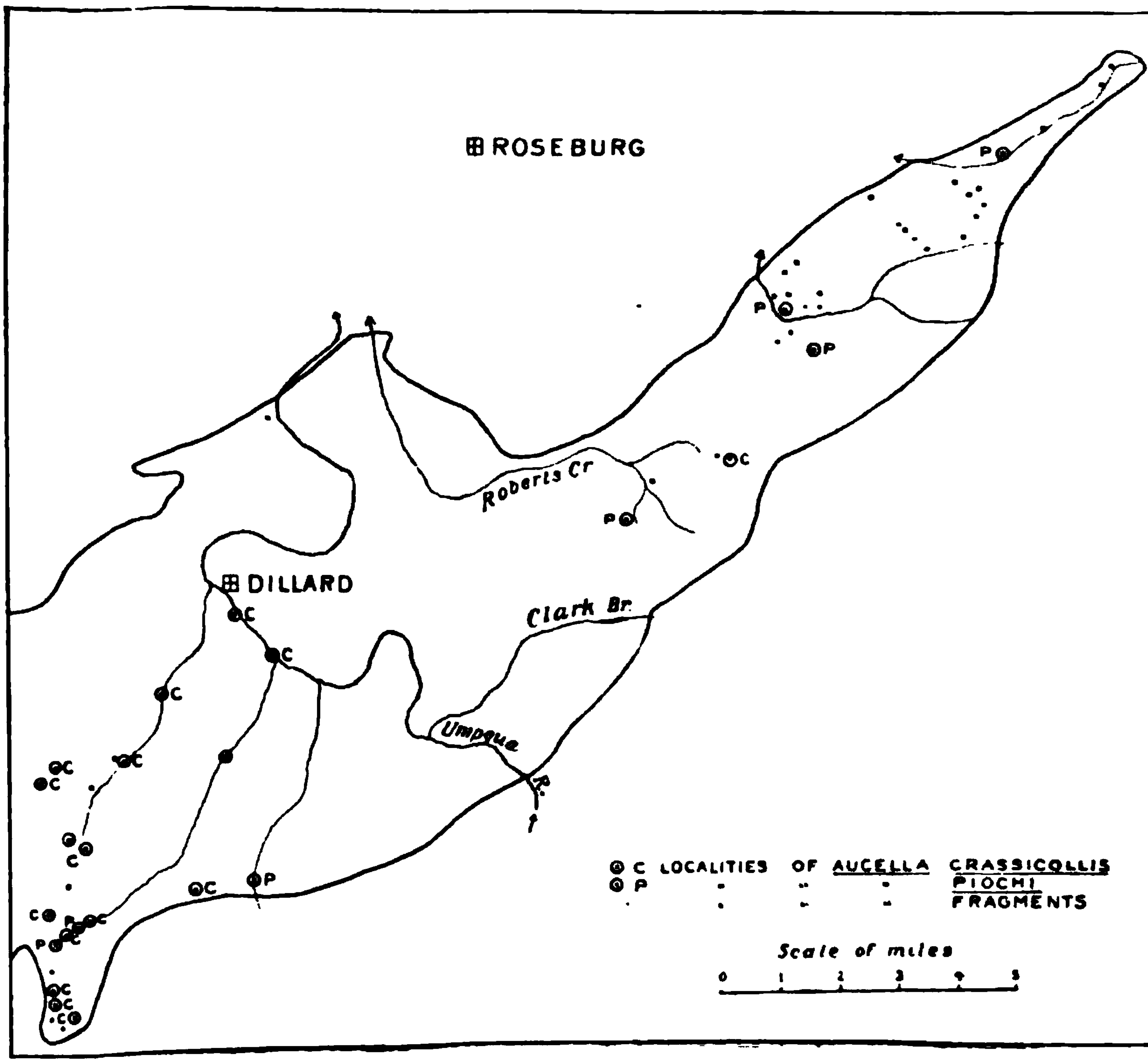

FIGURE 4.—*Dillard Area of Knoxville Formation*

LOCAL SILICIFICATION AT THE CLOSE OF THE KNOXVILLE

It is not claimed that the more general silicification of the Dothan took place at the same time as that of the Knoxville in the Dillard area, for

[10] It should be mentioned that there is some evidence recently observed concerning the relation of the glaucophane schists to the sedimentary rocks of the Dillard area. A conglomerate upon the right bank of the Umpqua river, a short distance below Winstons bridge, contains distinct pebbles of glaucophane schist and clearly indicates that the conglomerate is younger and lies uncomfortably on the schist. The conglomerate has been regarded as Knoxville, but no fossils could be found in it to prove its age. On the other hand, it lies on the side of the Dillard area adjoining the Eocene, and several areas of Eocene are now known to be included in the Dillard area as originally mapped.

the Knoxville where found in contact with the Dothan shows less silicification. Much of the silicification of the Dothan occurred before the deposition of the Knoxville, just as that of the Mariposa in California, but the silicification of the Knoxville of the Dillard area evidently occurred at a later epoch, most likely at the close of the Knoxville, for that was a time of deformation in the Dillard region.

It is interesting to note in this connection that in the Bohemia mining region, which lies in the same axis of deformation, 35 miles northeast of the Dillard area, there are large auriferous quartz veins in the Tertiary lavas of the Cascade range. The quartz veins of the Bohemia region are doubtless later than those of the Dillard area and demonstrate decided activity along the northeastern extension of this axis in Tertiary times. This fact facilitates the explanation of a considerable degree of silicification in the Dillard region at the close of the Knoxville.

Relation of the "Myrtle Formation" of Oregon to the Shasta Series of California

The areas of the "Myrtle formation" in Oregon are entirely disconnected from those of the Shasta series in California, so that their relation can not be determined by their contact, but must be inferred from their stratigraphic relation to associated rocks and their fossil contents.

Beneath the Shasta series, on the western side of the Sacramento valley, there is a conspicuous unconformity. The successively newer overlying beds of that series overlap to the eastward and cover the older highly tilted and somewhat altered pre-Shasta rocks. On the Cold fork of Cottonwood creek (near 7, figure 1) the great unconformity is between the Knoxville and the Paleozoic strata, farther northeast the Horsetown, and finally, about the northern end of the Sacramento valley, the Chico rests on the Paleozoic with conspicuous discordance.

The same general relation is shown on the southwest slope of the Klamath mountains. At Big Bar and Rattlesnake creek, localities 4 and 5, which are approximately on line northwest of 7, figure 1, there are isolated patches of strata which from their faunal relations belong to the Knoxville and rest with marked unconformity upon the Paleozoic rocks of that region. At Redding creek (6, figure 1), which is east of the line of Knoxville outcrop, the Horsetown beds rest on the Paleozoic strata, just as it does at the village of Horsetown in the Sacramento valley. The isolated masses of Shasta beds at 4, 5, and 6, figure 1, were once connected not only among themselves, but directly with the large mass of the Shasta strata along the western side of the Sacramento valley, forming a

continuous cover over the older rocks of the southern portion of the Klamath mountains.

This is demonstrated by the fact that the Shasta series of the Sacramento valley area extending northwest laps up over the crest of the Coast range (Klamath mountains) into the head of the Hay Fork country of Trinity river, where there are a number of small intermediate masses[11] of sandstone and conglomerate between those of Rattlesnake creek and Redding creek, showing that they were once connected by a continuous mass and joined across the crest of the range with the main mass of the Shasta in the Sacramento valley.

During the time the Shasta and Chico were deposited the Pacific border of the continent was subsiding and the sea transgressing the land. There may have been interruptions, perhaps slight elevations at several horizons within the epoch, as between the Knoxville and the Horsetown, which are locally unconformable, but the general movement was downward, with an advancing sea and successively newer marine deposits overlapping the earlier land.[12]

At the base of the "Myrtle formation" in Oregon there is an important unconformity and a decided overlap. The successively newer, overlying strata of the "Myrtle" in general lap over farther and farther inland beyond the limit of the older strata of the same series, just as the members of the Shasta series do in California. Furthermore, the lower portion and the greater part of the "Myrtle formation" is characterized by a fauna in large measure identical with that of the Knoxville beds, while the top part contains a fauna closely related to that of the Horsetown beds. There is good reason, therefore, for regarding the Shasta series of California and the "Myrtle formation" of Oregon as equivalent.

Distribution of the Shasta Flora in the "Myrtle Formation" of Oregon

In the "Myrtle formation" of Oregon there are two floras, the "flora of the Shasta" series and the "Jurassic flora of Oregon." They have not yet been definitely found together and their geographic distribution is significant.

The flora of the Shasta series has been reported by Ward and Fontaine in the vicinity of Riddle, Oregon, in a mass of the "Myrtle formation" connecting directly on the strike with that of the type locality on Myrtle

[11] O. H. Hershey's geological map of part of the Klamath mountains. Unpublished.
[12] Bulletin of the Geological Society of America, vol. 5, p. 453.

creek in the Roseburg quadrangle. In the Riddles area the following eight forms have been reported by Ward and Fontaine:

Sagenopteris mantelli ? Schenk.
Sagenopteris oregonensis Fontaine.
Sagenopteris nervosa Fontaine.
Angiopteridium strictinerve latifolium Fontaine.
Dionites buchianus abietinus Ward.
Nageiopsis latifolia Fontaine.
Populus ? *ricei* Fontaine.
Sapindopsis oregonensis Fontaine.

In this Riddles area of the "Myrtle formation" fossil plants are rare, but shells are quite abundant. The fauna, it is true, does not contain a large number of species, but they are characteristic, and the fauna and flora agree with the stratigraphy in correlating this area of the "Myrtle" with the Shasta on the western side of the Sacramento valley. The Riddles area, including the mass on Iron Mountain creek, is the only one in Oregon that has yet yielded the Shasta flora.

Distribution of the Jurassic Flora in the "Myrtle Formation" of Oregon

A line of deformation runs northeast and southwest through the region of Nickel mountain and Dodson butte. It follows a prominent ridge and appears to mark approximately the limit between the two floras of the "Myrtle formation." Southeast of it lies the Riddle region and Iron Mountain creek, where the "Myrtle formation" contains "the Shasta flora," while to the northwest of it lie the larger irregular areas of the "Myrtle," containing locally on Thompson creek and Elk river the "Jurassic flora of Oregon." At one point the line of deformation is overlapped by the Jurassic flora, where it reaches Cow creek at Nichols station.[13] In general, on account of the overlapping "Myrtle formation," it may be claimed that the "Myrtle" containing the Jurassic flora lying northwest of that containing the Shasta flora must be older. So it seems also from the entire abseuce of any Horsetown fauna on the northwest side of the axis in the same series near the Jurassic flora.

The most impressive fact in the field, knowing the distribution of the fossils, is the occurrence of ónly one form of Aucella with the Jurassic flora of Oregon. The flora probably extends far down in the portion of the "Myrtle formation" characterized by *Aucella piochi,* but no such

[13] Attention should be recalled to the Jurassic plant found in the Riddles area (see p. 373) and the one found in the Dothan (see p. 379). The last is the only one yet found in Oregon below the horizon of *Aucella crassicollis* and *Aucella piochi.*

association has yet been reported. The bulk of it appears to belong to the horizon of *Aucella crassicollis* not far below the base of the Horsetown.

Distribution of the Shasta and Jurassic Floras in the Klamath Mountains of California

If, as I believe, the isolated areas of plant beds at Redding creek, Rattlesnake creek, and Big Bar, on the west slope of the Klamath mountains, in Trinity county, California, are to be regarded as belonging to the Shasta series, then the Shasta series contains both floras; but, as in Oregon, they have not been found together and their geographic distribution is suggestive.

The Shasta flora is found widely but sparsely distributed in the beds along the western side of the Sacramento valley and, lapping over the crest of the range, appears in the Redding Creek basin, a few miles from Douglas City. The Jurassic flora of Oregon appears in the region here considered only at Big Bar and Rattlesnake creek. The position of these two localities suggests that the flora may yet be found close to the base of the formation in the Sacramento valley.

The occurrence of this flora at the very base of the overlapping beds with the little Unio connects the flora definitely with the subsiding coast and the transgressing sea during the Shasta epoch. As the Shasta epoch, with its great thickness of sediments, was a long one, the changes in the flora may have been great, and they would be recorded more or less completely in the successively newer overlapping strata. The changes in the environment of the flora may have been much greater and more effective than those of the fauna, so that in the course of the Shasta epoch the modifications of the flora may have been great, while of the fauna they were comparatively small.

Relation of the Monte de Oro Formation to the Mariposa

The slates of the Monte de Oro formation, as pointed out by Mr Turner,[14] "are very similar to those of the Mariposa formation," and it seems most probable, on geographic and structural as well as lithologic and economic grounds, that the plant beds near Oroville are about the same horizon as the Mariposa formation of the Gold belt. The fossils tend to confirm this correlation, but are not decisive. The extensive association of the slates with volcanic rocks in both the Monte de Oro formation and

[14] Seventeenth Annual Report of the U. S. Geological Survey, part 1, p. 548.

the Mariposa is striking and in strong contrast with the associated rocks of the later horizons in the Mesozoic.

Relation of the Monte de Oro and Mariposa Formations to the Knoxville

Stratigraphic Evidence

In California the Mariposa and the Knoxville are not found together. They outcrop on opposite sides of the Sacramento valley. The Mariposa is involved in the intense folding of the Sierra Nevada, is extensively associated with volcanic rocks, has been considerably metamorphosed, and contains important ore bodies which have been successfully mined. The Knoxville lies chiefly against the eastern slope of the Coast range and is not closely folded, altered, or associated with large masses of volcanics, as is the Mariposa. It rests unconformably on the strata which appear to have been folded with the Mariposa, and for this reason it is believed that if the Knoxville and Mariposa were found together in California they would be unconformable. This conclusion is in large measure confirmed in Oregon by the fact that the Knoxville rests unconformably upon the rocks which contain a fauna whose closest affinity is found in the Mariposa.

Faunal Evidence

It will be recalled that some years ago Dr C. A. White[15] regarded all the forms of Aucella yet discovered in the Northern Hemisphere as having "so close a generic relationship with one another as to hardly exceed the limits which may be reasonably assumed as those of a single species." Doctor White "became satisfied that the *Aucella piochi* of the Knoxville and *A. erringtoni* Gabb of the Mariposa belong to one and the same species," a conclusion which, as he states, "involved the opinion that at least a part of the series (Mariposa) is equivalent to the Knoxville." This opinion was accepted by Doctor Becker,[16] but has not been accepted generally by the paleozoologists and geologists who have studied the problem in the field.

Doctor Stanton, who has studied the faunas of the Knoxville and the Mariposa in the field more than any one else, is of the opinion that "the faunas, though not large, are entirely distinct, and that of the Mariposa includes several forms of ammonites that are characteristic of late Juras-

[15] U. S. Geological Survey Monograph XIII, pp. 226-232.
[16] U. S. Geological Survey Monograph XIII, p. 201.

sic the world over, while that of the upper part of the Knoxville contains an equally characteristic array of Cretaceous forms."

Vertical Range of Aucella and the two Floras in California and Oregon

In the accompanying diagram (page 369) is shown graphically the vertical range of the various forms of Aucella as well as the Shasta and Jurassic floras applied to the Oregon section. The "Myrtle formation" corresponds to the Shasta series, and the Galice formation probably corresponds to the Mariposa slates. These are separated by the Dothan formation,[17] which is conformable to the Galice, but unconformable to the overlying "Myrtle," and probably corresponds to the Franciscan of California. *Aucella erringtoni* characterizes the Galice and Dothan, which are conformable. *Aucella piochi* and *A. crassicollis* belong to the "Myrtle," which appears to be a conformable series throughout. The "Myrtle" and the Dothan are unconformable and the unconformity marks the final great folding of the Sierra Nevada.

The earliest Jurassic flora of Oregon occurs in the Mariposa (Monte de Oro), the equivalent of which in Oregon, judging not only from its lithology and fauna, but also from its associated volcanic rocks, is the Galice. A trace of the Jurassic flora I have reported from the Dothan, but a large part of it occurs in the "Myrtle," extending well up into the horizon of *Aucella crassicollis*.

The Shasta flora of the upper part of the "Myrtle" occurs throughout the Horsetown horizon and locally the greater part, if not the whole, of the horizon of *Aucella crassicollis* of the Knoxville. The two floras are marked in the diagram (page 369) as overlapping. They have not yet been found associated, but their geographic distribution and faunal relations strongly suggest such a possibility.

Limit between the Jurassic and Cretaceous

The close of the Jurassic on the Pacific coast has generally been regarded as marked by the great deformation and uplift that finally added the Sierra Nevada to the continent—a deformation marked by the unconformity between the "Myrtle" and the Dothan. This limit is an important structural feature and corresponds generally to the paleontologist's interpretation of the fauna, the Mariposa being Jurassic and the Knoxville Lower Cretaceous.

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[17] American Journal of Science, vol. xxiii, June, 1907, pp. 401-421.

With this view the paleobotanists are clearly not in agreement. They regard the beds containing the "Jurassic flora of Oregon" as earlier than the Cretaceous which contains the "Shasta flora." It has been shown in this paper that these two floras meet in the *Aucella crassicollis* zone in the upper part of the Knoxville. The exact line between the two floras, as far as yet known—and it has been the subject of study for some years—is not a distinct faunal line nor distinctly stratigraphic.

The position of the line between Jurassic and Cretaceous, as that line is defined in Europe and eastern North America, is perhaps determinable by the evidence of paleontology and paleobotany, but the ultimate basis of classification for the Pacific coast of the United States is the great unconformity at the base of the Knoxville (lower "Myrtle") formation.

SUMMARY

The "Jurassic flora of Oregon" described by Professors Ward and Fontaine occurs in the plant beds of Thompson creek and Cow creek near Nichols station. Careful search has been made at the localities mentioned, but its associated fauna is still a matter of doubt.

The same Jurassic flora has been found in the "Myrtle formation" closely associated with an upper Knoxville fauna at Elk river, in Oregon, and in the Knoxville at Big Bar and Rattlesnake creek, on the western slope of the Klamath mountains, in California.

The lower part of the "Myrtle formation" (Knoxville) in Oregon, though generally unaltered, is locally silicified and contains small veins of quartz.

The Cretaceous flora (Shasta) described by Ward and Fontaine from the large area of beds along the western side of the Sacramento valley has been increased in number of species and extended in geographic range by the collections recently made, but the flora is still regarded by Doctor Knowlton as Cretaceous and distinct from the Jurassic flora.

In the Riddles region of Oregon the Cretaceous flora occurs in the "Myrtle formation" and is associated with an upper Knoxville fauna like that found with the Jurassic flora at Elk river. In the Riddles area there has been found also one doubtful specimen of a species belonging to the Jurassic flora of Thompson creek and Elk river, and suggests a possible commingling of the two floras.

In Oregon only one doubtful specimen of the Jurassic flora has been discovered below the "Myrtle formation." It occurs in the Dothan. But in California, near Oroville, an extensive Jurassic flora has been reported in the Monte de Oro formation, where it is associated with a fauna that is probably Jurassic.

On geographic and stratigraphic grounds, but more especially on account of the associated volcanic rocks and ore bodies, the Monte de Oro formation is regarded as the equivalent of the Mariposa.

The strata containing the Jurassic flora of the Klamath mountains are conspicuously unconformable to the underlying Paleozoic rocks and contain not only a marine, but also a fresh-water fauna. They were deposited by the sea advancing over the slopes of the subsiding Klamath mountains.

The same is true of the strata containing the Cretaceous flora found along the western side of the Sacramento valley.

The two floras have not been found together, but both occur in strata which are lithologically the same, and from their geographic distribution, stratigraphic relation, and contained fauna belonging in part to the upper Knoxville.

The Cretaceous flora ranges from the upper Knoxville up to the top of the Horsetown, while the Jurassic flora ranges down into the Mariposa. One is confined wholly to the Cretaceous. The other occurs in the Cretaceous and ranges down into the Jurassic.

There is a lack of accordance in the faunal and floral evidence as to the position of the line between the Jurassic and Cretaceous. The paleobotanist would apparently place it somewhere in the upper part of the Knoxville, at a horizon which, as far as yet known, is not marked by any stratigraphic break. On the other hand, the faunal evidence, as interpreted by American paleontologists, places the line between the Mariposa and the Knoxville. This line is more definitely located as the great unconformity between the "Myrtle" and the Dothan, base of the Knoxville, and marks for the stratigraphic column of the Pacific coast one of the most important tectonic horizons.

GEOLOGIC MAP OF SOUTH-CENTRAL WYOMING

By N. H. Darton

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PALEOZOIC AND MESOZOIC OF CENTRAL WYOMING

BY N. H. DARTON[1]

(Read by title before the Society December 29, 1907)

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[1] Published by permission of the Director of the U. S. Geological Survey.
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GEOLOGIC MAP OF PART OF CENTRAL WYOMING

By N. H. Darton

INTRODUCTORY

During portions of the summers of 1905 to 1907 I made a reconnaissance of the geology of parts of central Wyoming, extending from the Colorado state line southwest of Laramie to the Wind River mountains northwest of Lander. Detailed geologic maps were made of much of the region lying east of longitude 107° and south of latitude 43°, and the Laramie and Sherman quadrangles of the U. S. Geological Survey were prepared for folio publication. In the western portion of the area I was assisted by Mr E. G. Woodruff, and most of the data in the region southwest of Laramie and Cheyenne were obtained for me by Mr C. E. Siebenthal. The work was a continuation southward of my explorations in the

Bighorn and Owl Creek uplifts, which have been published by the government.[2] [3]

It is the purpose of this memoir to present an outline of the results which throw light on the classification and general stratigraphy of formations from Cambrian to Cretaceous in age. Tertiary deposits exist throughout the area examined, but only passing attention was given to their features, and the various formations are not differentiated on the geologic map, plate 21.

General Geology

The sedimentary rocks of central Wyoming represent parts of Cambrian, Ordovician, and Jurassic time and nearly all of Carboniferous, Cretaceous, and Tertiary time. The Triassic apparently is represented also, but only in part. The table on page 407 is a list of the formations, with brief notice of their character and ordinary range in thickness. Some general comparisons of the stratigraphy are shown in plate 23.

General Stratigraphy

The pre-Cambrian rocks are overlain unconformably by the Cambrian and later sedimentary rocks, and in most places were planed very smooth before the sediments were laid down. Although some of the Paleozoic and Mesozoic strata are separated by erosion unconformities, no discordance of dip is perceptible. The Deadwood formation, representing a portion of middle Cambrian-Acadian time, is present throughout northern and central Wyoming, but does not extend into the Laramie Mountain region. The Bighorn limestone, the product of part of Ordovician time, is restricted to the Wind River-Owl Creek and central and northern Bighorn regions. Silurian and Devonian do not appear. The Carboniferous comprises the Pennsylvanian and Mississippian divisions in the greater part of the region, but the latter thins out to the south and ceases in Laramie mountains along a line not definitely located. This line crosses the range not far from the canyon of Laramie river. The Pennsylvanian division, which consists mainly of shales and sandstones in northern Wyoming, contains thick bodies of limestone east of longitude 107°, but on both sides of Laramie mountain south of the latitude of Laramie these mostly give place to sandstone largely of red color. The Chugwater red beds, consisting of fine-grained bright red sediments, with gypsum deposits and thin limestone layers, underlie the entire area. The marine

[2] U. S. Geological Survey Professional Paper no. 51. Washington, D. C., 1906.
[3] 51st Congress, 1st session, Senate Executive Document no. 219. Washington, 1906.

Montana
upper division

Montana
lower division
(Pierre shale)

Colorado

Cloverly
Morrison
Sundance

Chugwater

Embar
Tensleep
Amsden

Madison

Bighorn

Deadwood

Granite, gneiss etc.

COLUMNAR SECTIONS OF CENTRAL WYOMING

N, Niobrara; M, Mowry beds; G, Greenhorn limestone; F, Forelle limestone on Satanka shale; C, Casper formation; XX, Gypsum; P, Parkman sandstone

Period.	Formation.	Characteristics.	Thickness.
			Feet.
Miocene	Arikaree	Soft sandstone, gravel, conglomerate.	0–1,000
Oligocene	Brule	Massive sandy clay, mostly pale buff.	0–400
	Chadron	Sand, clay, and sandstone, mostly light.	0–100
Eocene	Bridger-Wasatch	Soft sandstone—red, gray, green.	1,000±
Cretaceous	Laramie, etcetera.	Coarse buff to gray sandstone, gray shale.	4,000±
	Fox Hills-Mesa Verde.	Sandstone, local coal beds	
	Pierre	Dark shale with concretions.	3,000+
	Niobrara	Limestone, chalk, and limy shale, grading into shale to northwest.	100–450
	Benton	Gray shale; buff sandstone and concretions near top; hard shales (Mowry beds) near middle.	800–1,200
	Cloverly: Dakota	Buff sandstone	50–150
	Cloverly: Fuson	Gray to purple shale or clay.	
	Cloverly: Lakota	Massive buff sandstone, conglomerate near base.	
(?)	Morrison	Massive shale—pale green, gray, maroon; thin limestone and sandstone.	100–250
Jurassic	Sundance	Soft buff sandstones; green shales with hard fossiliferous layers.	0–250
Permian-Triassic (?)	Chugwater	Red shale and soft red sandstone; thin limestones, and gypsum deposits.	800–1,250
Carboniferous	Embar	Gray limestone, buff shale, cherty beds.	50–250
	Tensleep[1]	Massive, gray, cross-bedded sandstone.	30–300
	Amsden[1]	Red shale overlain by shale, sandstone, and cherty limestone.	100–300
	Madison[1]	Limestone, light colored, massive near top.	0–1,000
Ordovician	Bighorn	Hard, massive, pale buff, siliceous dolomite.	0–150
Cambrian (Middle)	Deadwood	Brown sandstone, gray shale, flat pebble limestone conglomerate, and limestone.	0–800
Pre-Cambrian	Granite, gneisses, etcetera.	...	...

[1] From the Casper range southward these three formations give place to the Casper formation, 500 to 1,000 feet thick, consisting of limestones generally lying on and overlain by gray sandstone. In the Laramie region and southward these rocks merge into red grits.

Jurassic which follows is similar to that of the Black hills and northern and western Wyoming, but it thins out to the south at an unknown point a few miles southeast of Medicine Bow. The next formation, the Morrison shale, with an average thickness of 200 feet, is persistent throughout, together with the overlying Cloverly sandstone, the latter representing the "Dakota" of earlier writers. The great series of upper Cretaceous shales attains a thickness of 5,000 feet or more and occupies broad basins between the great uplifts. At the base is the Benton shale, which lacks its medial limestone member (Greenhorn) excepting along the southeast side of the Laramie mountains. The Mowry beds and upper sandstone are, however, prominent throughout. West of longitude 107° the limy deposits of the Niobrara give place to shale. The Montana consists of a lower division of dark shale with all the characteristics of the Pierre, and an upper member of sandstone similar to the Fox hills of other regions. This sandstone is followed by coal measures and shales of Montana age, overlapped by sandstones which are regarded as Laramie. The Tertiary occupies wide areas on some of the tabular divides and attains considerable thickness in the Wind River basin. The formations are mostly Wasatch, White River, and Arikaree. They lie across upturned edges of the earlier formations. The Quaternary is represented by old terraces, which are of great extent in the Laramie basin, and by alluvial flats in the present valleys.

Cambrian System

DEADWOOD FORMATION

General relations.—The sandstone of the Deadwood formation is at the base of the sedimentary series in northern and central Wyoming. It thins out to the southeast and apparently ceases at no great distance east of longitude 107°, so that in Converse, Albany, and Laramie counties the Carboniferous rocks lie directly on pre-Cambrian granites and schists. In the Shirley hills a hard, massive sandstone and conglomerate underlying Madison limestone may be Deadwood. On the West fork of Troublesome creek, 9 miles northwest of Difficulty post-office, and about Leo, this sandstone, 30 feet or more thick, is hard and in part conglomeratic. Near North Platte river, north of the mouth of the Medicine Bow, it is about 100 feet thick. Whether in these areas it is a shore deposit of Madison age or the Deadwood formation was not ascertained. In the basal sandstone in the gorge of North Platte river, 3 miles northeast of Pathfinder, Mr Walcott found a few fragmentary fossils which he regards as Cambrian. The hard sandstone at the base of the sedimentary series

in the Casper range and in the ridges to the southeast appears to be a shore deposit of the Casper formation.

Rattlesnake mountains.—The Deadwood formation outcrops along a portion of the crest of Rattlesnake mountains west of Oil City. It is about 800 feet thick. At the base and near the middle are 25 to 40 feet of brown to buff fossiliferous sandstone and the basal beds are somewhat quartzitic. Sandy gray shale with thin gray sandstone layers constitute the greater part of the formation, but there is a small amount of impure slabby limestone and reddish shale near the top. Glauconite is a conspicuous ingredient in most beds.

Wind River mountains.—On the northeast slope of Wind River mountains the Deadwood formation is about 750 feet thick, and it presents all the features which are characteristic in the Bighorn and other ranges northeastward. Its presence was recognized by Comstock[5] and its distribution was shown in part on maps of the Hayden Survey.[6]

The basal member, which lies on granite, is about 100 feet thick and is the usual hard, brownish sandstone. Next are sandy shales and slabby limestone, the latter including more or less of the typical flat pebble conglomerate of gray limestone pebbles covered with glauconite. The top layer of this limestone contains many trilobites. At the top of the formation is a hard, coarse, fossiliferous sandstone.

Owl Creek mountains.—Extensive exposures of the Deadwood formation extend along the upper slopes of Owl Creek mountains and in the canyon of Bighorn river. It also appears along Crow creek northeast of Circle and in Owl Creek canyon. The thickness is 900 feet and the succession of rocks is similar to that in the Bighorn and Wind River mountains. At the base is hard, coarse-grained, reddish brown sandstone, locally conglomeratic below and lying on a remarkably smooth plain of the pre-Cambrian rocks. It varies from 50 to 100 feet in thickness and is succeeded by 200 to 300 feet of sandy shales and thin-bedded sandstones, with a prominent bed of sandstone in their lower portion. In Bighorn canyon this bed is 50 to 60 feet thick and of bright reddish brown color. The medial member is 400 feet or more of soft greenish gray shale with a conspicuous gray to buff limestone in its lower part. This limestone, usually 50 feet thick, consists partly of flat pebble limestone conglomerate. Southwest of Embar it is 30 feet thick and 300 feet above the base of the formation. At the head of Muddy creek it is 40

[5] Report on Reconnaissance of Northwestern Wyoming, 1873, by W. A. Jones (War Department), 43d Congress, 1st session, House of Representatives Executive Document no. 285. Washington, 1874.

[6] Twelfth Annual Report U. S. Geological and Geographical Survey of the Territories for 1878, Atlas. Washington, 1883.

feet thick and underlain by a somewhat thicker mass of sediments. The top member of the formation is slabby light colored limestone over 100 feet thick at most localities, but apparently either very thin or absent in Owl Creek canyon. It contains frequent layers and masses of the characteristic intraformational conglomerate of flat limestone pebbles more or less intermingled with thin, twisted, and broken layers of limestone in a matrix of shale and fine limestone sand. Many of the pebbles are so thickly covered with grains of glauconite that they appear to be green, but inside they are gray or pinkish, similar to the associated beds.

Fossils.—Fossils at various horizons in the Deadwood formation are of middle Cambrian age, and *Dicelamus politus* and *Ptychoparia oweni* are the principal forms. The former is a small oval shell, which occurs in great abundance in the middle sandstones and in the limestone layers in the shales, as well as in the upper limestone series. The *Ptychoparia* is a trilobite which often abounds in the basal sandstone. In the middle sandstone of the formation, a short distance west of Garfield peak of Rattlesnake mountains, the fossils included a new species, which Mr Walcott has designated *Obolus* (*Westonia*) *dartoni*. In the top sandstone west of Lander, *Orthis* (*Plectorthis*) *wichitaensis* was found.

Ordovician System

Bighorn Limestone

General relations.—In 1905 I presented to this Society all available facts as to the distribution of the Ordovician in the Northwest.[7] In the following summer Mr Woodruff and I examined the Bighorn limestone in the Wind River mountains. The formation terminates at the south end of that range and is absent in the Rattlesnake, Casper, Medicine Bow, and Laramie mountains as well as in the southeastern portion of the Bighorn mountains.

Wind River mountains.—The "Silurian" limestone, first recognized in Wind River mountains by Comstock and also shown on the maps of the Hayden Survey, is the Bighorn limestone. It lies between the Deadwood formation and Lower Carboniferous (Madison) limestone all along the east slope of the range and presents prominent exposures, especially in the canyons. It has the characteristics, which are distinctive in the Bighorn mountains, of a hard, massively bedded, impure dolomite with considerable silica streaked through it. It gives rise to a low cliff and on weathering breaks off in huge, rectangular blocks which in places accumu-

[7] Bulletin of the Geological Society of America, vol. 17, pp. 541-566.

late on the slopes of the Deadwood formation. On Dinwoody creek the massive dolomite, 50 feet thick, lies on 100 feet of shaly limestone that is very sandy.

Owl Creek mountains.—In the eastern part of the Owl Creek uplift the Bighorn limestone is about 40 feet thick; in Phlox mountain and Owl Creek canyon it is over 150 feet, and near Crow creek it is about 100 feet thick. The outcrop is continuous around the higher central area of the uplift, and it extends westward along South fork of Owl creek to a point 3 miles west of longitude 109°. It shows again on the slopes adjoining Crow Creek canyon and the upper portion of West fork of Muddy creek and in Bighorn canyon. The most prominent exposures are in the great escarpment of Phlox mountain. It is a hard, massively bedded dolomite, mostly of a light buff color, but somewhat darker when weathered, filled with a coarse network of irregular siliceous masses, mostly from a half to 1 inch in diameter. On weathering, this material stands out half an inch or more on the rock surface as a ragged network, the purer rock between having been dissolved. This feature and the very massive bedding are characteristic. In Owl Creek canyon the massive limestone is overlain by 20 feet of white limestone, capped by a 20-foot massive bed similar to the thick limestone below, while at the top of the formation there are a few feet of sandstone and shale. In places these upper beds weather to a reddish tint, strongly suggestive of the member of Richmond age which occurs in the northern portion of the Bighorn uplift. The appearance of two of the most prominent outcrops in the Owl Creek canyon is shown in plates 76 and 77 of my memoir on Ordovician of the Northwest.[8]

Fossils and age.—Fossils usually are rare in the Bighorn limestone, consisting mostly of fragments of maclurina and corals. At one locality in the Wind River mountains, however, Mr Woodruff obtained an extensive fauna from the basal calcareous sandstone, which was determined by Mr E. O. Ulrich as follows: *Receptaculites oweni* Hall; *Streptelasma* cf. *profundum* Conrad and *corniculum* Hall; a ramose bryozoan resembling *Callopora multitabula* Ulrich; *Plectambonites sericius*, var. *Dalmanella testudinaria*, var. *Strophomena*, n. sp. near *S. sulcata* Vern. and *S. fluctuosa* Billings; *Ctenodonta* cf. *levata* Hall; *Cyrtodonta* cf. *rotulata* Ulrich; *Psiloconcha* n. sp.; *Archinacella* cf. *A. deleta* Sard. and *A. subrotunda* Ulr.; *Protowarthia* cf. *cancellata* Hall; *Lophospira*, near *L. elevata* Ulr.; *Trochonema umbilicatum* Hall; *Hyolithus* cf. *baconi* Whitfield; *Chiton canadensis* Billings; *Orthoceras*, near *O. olorus* Hall and *O. nicol-*

[8] Loc. cit.

leti Clarke; *Actinoceras* cf. *remotiseptum* Clarke. This fauna is regarded as late Black River and early Trenton by Mr Ulrich, for identical or closely related forms occur in Black River and Trenton rocks in New York. He correlates the horizon with the lower massive limestone and its underlying sandstone in the Bighorn mountains and with the Harding sandstone and the lower (Galena-Trenton) portion of the Fremont limestone of the Canyon City region in Colorado. The hiatus at the top of the Bighorn limestone represents a part of Ordovician and all of Silurian and Devonian time, but there are no marked features of a great unconformity in the contact of the Bighorn and Madison limestones.

Carboniferous System

Madison Limestone

General relations.—The Madison limestone is very prominent in the Bighorn, Wind River, and Owl Creek mountains and it is distinct in the Rattlesnake mountains and the region south of Alcova. It disappears in the Laramie mountains where the Casper formation lies directly on the pre-Cambrian rocks.

Wind River mountains.—Northwest of Lander the Madison limestone is from 250 to 300 feet thick, and it constitutes the crest and part of the long eastern slope of the prominent foothill range. The rock is light gray, pure and very massive in its upper portion, but darker, more slabby, and with considerable chert in its lower member.

Owl Creek mountains.—The Madison limestone outcrops in the higher portion of the Owl Creek uplift, ordinarily constituting a prominent flanking ridge and causing high cliffs in the canyon walls. It averages from 500 to 600 feet thick and consists of moderately thick-bedded gray limestones with an upper member of massive light colored limestone which weathers to a light dove color. This upper member is cavernous and in many places weathers in pinnacles and castellated forms. Extensive exposures appear in and near Bighorn canyon and at intervals in the higher ridges to the west, notably in the vicinity of Phlox mountain, Owl Creek canyon, and Black mountain.

Rattlesnake mountains-Shirley hills.—The Madison limestone is 250 feet thick on the north slope of Rattlesnake mountains, where it outcrops for 7 or 8 miles. The rock is a massive, light gray limestone, presenting most of the features observed in other regions and yielding distinctive fossils. In the canyon of Platte river, between Pathfinder and Alcova, the limestone again appears, but the precise thickness was not ascertained. It lies between sandstone below and red shale of Amsden formation above. These features appear again southeast of Pathfinder and

about Leo. Three miles southeast of Leo the red shale, supposed to represent the basal member of the Amsden formation, is underlain by 110 feet of hard limestone. A few miles farther east, near Shirley, this lower limestone is 75 feet thick, while on the south side of the Shirley hills, at a point 9 miles west-northwest of Difficulty, there are about 400 feet of limestone under the red shale. The upper portion of this limestone is white, fine-grained, massive, weathers light dove-colored, and erodes in pinnacled forms, features which characterize the upper member of the Madison limestone in the Bighorn mountains.

Fossils.—The Madison limestone is sparingly fossiliferous, and *Spirifer centronatus, Seminula humilis,* and *Chonetes loganensis* are the species of most frequent occurrence. Dr G. H. Girty has determined the following from the head of Sage creek, on the Shoshone reservation, northwest of Lander: *Schuchertella inflata ?, Chonetes illinoisensis, Productus* sp., *Spirifer centronatus, S. striatus,* var. *madisonensis,* and *Seminula humilus ?.* From the Madison limestone on north slope of Rattlesnake mountains a short distance west of Garfield peak the following were identified: *Zaphrentis* sp., *Fenestella* sp., *Schuchertella inflata ?, Chonetes illinoisensis, Productus lævicosta, Spirifer centronatus, Spiriferina solidivostris, Cleiothyris crassicardinalis ?, Camerotœchia* sp., *Modiola ?* sp., *Straparollus luxus, S.* aff. *obtusus, Bellerophon* sp., *Prœtus* sp., and an ostracod undetermined.

From near the base of the limestone 3 miles southeast of Leo many fragments were collected, among which Doctor Girty has determined *Spirifer striatus* var. *madisonensis* and a *Cleiothyris ?* sp.

The fossils indicate that the formation is of Mississippian age, equivalent to the Madison limestone of Montana and the Pahasapa limestone of the Black hills.

AMSDEN FORMATION

General relations.—The red shale, sandstone, and cherty limestone of the Amsden formation extend along the northeast slope of the Wind River range, and they appear also on Rattlesnake mountains and on North Platte river south of Alcova. In the Casper and Laramie mountains where the formation is much less characteristic, it is included in the Casper formation.

Owl Creek mountains.—In the Owl Creek uplift the Amsden formation varies from 200 to 250 feet in thickness, and it outcrops along both slopes of the range, excepting locally where it is cut by faults. It surmounts cliffs of Madison limestone in Bighorn canyon and along the south front of the mountain westward nearly to the Lander-Thermopolis road, and is prominent on the east slope of Black mountain and the ridge

next north. There is always a lower member of red shale about 50 feet thick containing thin beds of fine-grained, white limestone. In most places this red shale lies on Madison limestone, but west of Anchor it is separated by gray sandstone. The middle and upper members are sandstones and limestones, the latter cherty, especially near the top.

Wind River mountains.—The Amsden outcrop is about half way up the slopes of the front range of Wind River mountains. The basal red shales are about 75 feet thick, and the upper member is a yellow limy shale, which is only 25 feet thick near Bull and Willow creeks.

Rattlesnake mountains and eastward.—In Rattlesnake mountains the interval between Madison limestone and Tensleep sandstone is about 250 feet. I found no good exposures of the intervening beds excepting of the red shale, which is 60 feet thick. Next above are slabby sandstones and cherty limestones.

In the Shirley and Alcova uplifts and in portions of the northern extension of the Laramie uplift the Amsden red shale is distinct, but it is overlain by gray limestone, which is not typical of the Amsden. In exposures 9 miles west-northwest of Difficulty the red shale is 40 feet thick and underlain by 400 feet of limestone, probably Madison. Fifteen miles northwest of Difficulty, where the red shale is 25 feet thick, it is overlain by 80 feet of limestone and underlain by 75 feet of limestone, the latter probably Madison. Southeast of Leo, where the red shale is 80 to 100 feet thick, there are 55 feet of limestone above and 110 feet of limestone below. In the northwest corner of Albany county the red shale is separated from the granite by a small amount of sandstone and overlain by limestones of which the lower 100 feet are cherty. At a point 5 miles north-northwest of Marshall, where the red shale is 30 feet thick, it is separated from the granite by only 1 to 2 feet of sandstone. There is strong suggestion here of lateral overlap of the Amsden southward across the edge of the Madison limestone, for the latter is absent to the south.

Fossils and age.—Fossils are rare in the Amsden in central Wyoming, but in the Bighorn uplift the upper beds yielded Pennsylvanian species, while a few supposed Mississippian forms occur in limestones in the basal red shales. Accordingly it is believed that the formation comprises part of both divisions of the Carboniferous. A few fossils obtained from basal beds of the Casper formation 7 miles northwest of Marshall post-office were determined by Doctor Girty as *Spirifer centronatus, S. cameratus,* ? and *Straparollus utahensis,* which are regarded as Mississippian. The rocks are cherty limestones lying on red shales strongly suggestive in appearance of the Amsden formation of the Bighorn mountains.

In the upper limestone member, 5 miles southeast of Leo, which is in Amsden formation, the following species were found: *Chonetes flemingi, Productus nebraskensis, P. cora, Aviculipecten occidentalis,* and *Allerisma terminale*. In limestone of about the same horizon, just above red shale, 1½ miles southwest of Shirley post-office, or 15 miles north-northwest of Difficulty, the fossils obtained are *Archæocidaris,* aff. *megastylus, Chonetes flemingi, ? Productus cora, P. portlockianus,* and *Seminula subtilita.*

TENSLEEP SANDSTONE

General relations.—In most portions of Wyoming the Carboniferous limestones are overlain by a thick body of sandstone which generally gives rise to a flanking ridge of considerable prominence. It has been designated the Tensleep sandstone from the typical locality in the Bighorn mountains and probably represents the upper sandstone of the Minnelusa formation in the Black hills. It is conspicuous in the Owl Creek, Wind River, and Rattlesnake uplifts and the ranges constituting the northern extension of the Laramie mountains, but locally in Laramie basin and eastward it is less distinct.

Owl Creek mountains.—The thickness of the Tensleep sandstone is uniformly 200 feet or slightly more in Owl Creek mountains. In the east end of the uplift it outcrops at or near the top of the mountains and it extends far northward in the canyon of Bighorn river. In the low divide, where the Lander road crosses the mountains, the formation presents a complete arch, constituting the summit. Farther west the sandstone extends along the flanks of the mountains, and extensive exposures occur south of Middle fork of Owl creek, in the anticlinal ridge east of longitude 109° and on the east slope of Black mountain. Most of the rock is white to buff sandstone, in thick massive beds, in greater part cross-bedded. Locally the color of the weathered surface is very dark, particularly near the Lander road and in the vicinity of Middle fork of Owl creek.

Wind River mountains.—The Tensleep sandstone constitutes a prominent ridge extending along the slope of the limestone foothills of the Wind River range. In the canyons of the many streams flowing out of the mountains the formation is marked by cliffs of considerable height presenting very massive ledges. The rock is cross-bedded, massive sandstone locally iron-stained and averaging 350 feet thick. Its thickness near Circle is estimated at 550 feet.

Rattlesnake mountains.—Much of the upper slope on the northeast side and northwest end of Rattlesnake mountain consists of Tensleep sandstone, which is about 150 feet thick. Most of the rock is quartzitic and weathers dark.

North Platte basin and southward.—The uppermost member of the Casper formation in Natrona and Converse counties and southward is a hard, massive sandstone, often 100 feet or more thick, which is believed to be an extension of the Tensleep. It is conspicuous at the east end and along the south side of Casper mountain and from the head of Muddy creek eastward, notably on La Prele creek, where it constitutes the natural bridge, and on Wagonhound creek 10 miles south by west of Douglas. South of Marshall it is 100 feet thick and rises in high knobs, and its outcrop is wide in the anticline 12 to 15 miles southwest of Garrett. It constitutes "Flat Top," a high ridge on the axis of the anticline 6 miles north of Medicine Bow. It is from 100 to 150 feet thick along the east side of Shirley hills, from Troublesome creek to the head of Muddy creek, and appears extensively in the anticline north and west of Difficulty as well as in two anticlines east of that place. The sandstone is about 150 feet thick in the canyon of Platte river, 5 miles above Alcova, and it is brought up again by a beautiful anticline through which the river cuts a gorge just above Alcova (see plate 24).

Age.—No fossils were observed in the Tensleep sandstone in central Wyoming, but in the Bighorn mountains it contains a Pennsylvanian fauna.

EMBAR FORMATION

General relations.—In the Owl Creek and Wind River uplifts and for some distance southeast the Tensleep sandstone is separated from the Chugwater red beds by a series of limestones and cherty beds from 150 to 250 feet thick, which has been designated the Embar formation. It appears not to extend into the Platte River region, excepting one or two doubtful occurrences.

Owl Creek uplift.—In the Owl Creek uplift the Embar formation varies from 200 to 250 feet thick. It outcrops along both sides of the Owl Creek mountains and the north side and east end of the Bridger range. The most prominent exposure is in the great dip slope adjoining Bighorn canyon, a few miles south of Thermopolis, where an upper limestone 50 feet thick constitutes the surface for many square miles. The formation is also extensively exhibited along the mountain slopes near the head of Muddy creek, along the line of outcrop extending through Anchor, and in the anticline southeast of Embar. It appears again in the more elevated portion of the anticline which passes through Thermopolis. The limestone in the canyon walls south of Thermopolis is 50 feet thick, of gray color, moderately massive bedding, and of considerable hardness. It is underlain by about 100 feet of shale, partly limy, filled with oval concretions of chert mostly from 1 to 2 inches in diameter.

FIGURE 1.—TENSLEEP SANDSTONE IN ANTICLINE CUT BY NORTH PLATTE RIVER JUST ABOVE ALCOVA, WYOMING. LOOKING SOUTH

FIGURE 2.—VIEW LOOKING NORTH OUT OF NORTH PLATTE CANYON, 5 MILES SOUTH OF ALCOVA, WYOMING

Tensleep sandstone in foreground, sinking into Red Bed valley. Canyon through anticline at Alcova in distance

TENSLEEP SANDSTONE

Next below are alternations of limestone and shale, 25 feet or more in thickness, lying on a thin deposit of sandstone breccia, which in turn lies on Tensleep sandstone. At the foot of the mountain slope the limestone member is seen to pass under yellowish sandy beds containing a few thin, impure layers of limestone, in all from 50 to 60 feet thick. Near North fork of Muddy creek, where the total thickness is 250 feet, the 50-foot limestone is overlain by nearly 100 feet of shale containing a large amount of nodular chert and a thinner massive limestone. Toward the top the beds are sandy and in most places of a bright yellow color. In the anticline on the south side of the mountains, 2 miles east of longitude 109°, the following section was measured:

Section of Embar Formation near Muddy Creek, 2 Miles East of Longitude 109°

	Feet
Compact gray sandstone, weathering brown, merging downward into brownish gray and yellowish soft sandstone...	50
Light colored massive limestone..........................	30
Nodular dark colored limestone, in part cherty............	80
Dark gray fossiliferous sandstone........................	4
Light buff colored soft sandstone, with layers of limestone, lying on Tensleep sandstone............................	60
Total.......................................	224

In the vicinity of Embar the massive limestone member is 50 feet thick, and near Anchor post-office it is overlain by 25 feet of soft buff sandstone. On Dry creek, 6 miles northeast of Black mountain, the formation is much thicker than observed in other places. The basal sandstones and limestones thicken to 200 feet, while the limestone member elsewhere near the top of the formation is 30 feet thick and overlain by over 200 feet of slabby brown sandstones, with some layers of buff soft sandstone. The latter extend to the base of the Chugwater red beds.

Wind River mountains and eastward.—Near Sage creek, on the north slope of Wind River mountains, the Embar formation presents the following beds:

Section of Embar Formation West of Fort Washakie, Wyoming

	Feet
Shaly limestone	2
Yellow shale	25
Sandstone	4
Yellow shale	75
Limestone, cherty in upper and lower parts; many fossils..	30
Yellow shale	40
Limestone (on Tensleep sandstone).......................	10
Total.......................................	186

On the northeast slope of Rattlesnake mountains the Tensleep sandstone is separated from the Chugwater red beds by buff shale and thin layers of pure limestone which probably represent the Embar formation. The only trace of this formation observed in the region eastward is in the local anticline just west of Difficulty post-office, where the Tensleep sandstone is overlain by 250 feet of yellow shales and limestones strongly suggestive of the Embar formation in the Owl Creek mountains.

Fossils and age.—The massive limestone member of the Embar formation is very fossiliferous, especially in the walls of Bighorn canyon south of Thermopolis, but, so far as observed, there is only one mollusk, identified by Dr G. H. Girty as *Spiriferina pulchra.* This form is believed to characterize a horizon just below the so-called Permo-carboniferous of the Wasatch Mountain region, and, as Doctor Girty correlates the latter with the Permian of the Grand Canyon section, the occurrence of these fossils in the Embar limestone suggests that this formation is equivalent to the upper Aubrey limestone of northern Arizona. A fenestelloid which could not be determined specifically also occurs in this limestone.

The fossils obtained by Mr Woodruff on the slope of the Wind River mountains on head of Sage creek were found by Dr G. H. Girty to be *Spiriferina pulchra, Seminula subtilita, Aviculipecten* aff. *eruekensis, Stenopora* sp., *Polypora* sp., *Derbya ?* sp., and a sponge. From ledges west of Lander there were obtained *Spiriferina pulchra, Spirifer* aff. *cameratus,* and *Productus nevadensis ?.*

According to Doctor Girty, "The Embar limestone has a very different fauna from the Kansas Permian, but it may be equivalent to it or even later. The fauna is not related to Guadaloupian. It occurs in Utah just below Permo-Carboniferous and is known also in Idaho and Nevada."

CASPER FORMATION

Name and general relations.—The name Casper formation is proposed for the limestones and sandstones constituting the greater part of the sedimentary rocks in the Casper and Laramie mountains. These rocks represent the southeastward extension of the Amsden and Tensleep formations, but are so changed in character and indefinite in stratigraphic limits that correlation is not desirable and a new name is required. The Casper formation lies on pre-Cambrian rocks in the greater part of the area, but possibly to the north the basal sandstone represents an attenuated eastern extension of the Deadwood formation, and in eastern Carbon and Natrona counties there may also be a small amount of Madison limestone at the base, but at present there is no evidence on which to separate these. The plane on which the formation lies rises to the south,

North Platte basin and southward.—The uppermost member of the Casper formation in Natrona and Converse counties and southward is a hard, massive sandstone, often 100 feet or more thick, which is believed to be an extension of the Tensleep. It is conspicuous at the east end and along the south side of Casper mountain and from the head of Muddy creek eastward, notably on La Prele creek, where it constitutes the natural bridge, and on Wagonhound creek 10 miles south by west of Douglas. South of Marshall it is 100 feet thick and rises in high knobs, and its outcrop is wide in the anticline 12 to 15 miles southwest of Garrett. It constitutes "Flat Top," a high ridge on the axis of the anticline 6 miles north of Medicine Bow. It is from 100 to 150 feet thick along the east side of Shirley hills, from Troublesome creek to the head of Muddy creek, and appears extensively in the anticline north and west of Difficulty as well as in two anticlines east of that place. The sandstone is about 150 feet thick in the canyon of Platte river, 5 miles above Alcova, and it is brought up again by a beautiful anticline through which the river cuts a gorge just above Alcova (see plate 24).

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Owl Creek uplift.—In the Owl Creek uplift the Embar formation varies from 200 to 250 feet thick. It outcrops along both sides of the Owl Creek mountains and the north side and east end of the Bridger range. The most prominent exposure is in the great dip slope adjoining Bighorn canyon, a few miles south of Thermopolis, where an upper limestone 50 feet thick constitutes the surface for many square miles. The formation is also extensively exhibited along the mountain slopes near the head of Muddy creek, along the line of outcrop extending through Anchor, and in the anticline southeast of Embar. It appears again in the more elevated portion of the anticline which passes through Thermopolis. The limestone in the canyon walls south of Thermopolis is 50 feet thick, of gray color, moderately massive bedding, and of considerable hardness. It is underlain by about 100 feet of shale, partly limy, filled with oval concretions of chert mostly from 1 to 2 inches in diameter.

so that the lowest beds included in the northern part of the area are not present at Laramie and southward. The Casper formation caps Casper mountain and the series of high ridges extending from east of Freeland nearly to Douglas. It extends along both slopes of Laramie mountains, but in places it is hidden by Tertiary deposits, especially in the northwestern part of Laramie county. It extends around the south end of Laramie basin and along the west side of that basin as far north as Jelm mountain, beyond which it is dropped far beneath the surface by the great fault which follows the east side of Medicine Bow mountains. It occurs in the syncline of Centennial valley and appears in the uplifts of Freezeout and Shirley hills and south of Alcova, but in the latter region and in the Rattlesnake mountains and westward the Carboniferous can be subdivided into Madison, Amsden, and Tensleep formations.

For the greater part of its course the Casper formation consists mainly of 300 to 400 feet of massive limestone and dolomite of light color, with gray sandstone at its top and base. To the north of latitude 42° there is often a red shale member near its base. Excepting near Laramie, it is sharply separated above from the red shales of the Chugwater formation. The basal sandstone lies on the pre-Cambrian. Near the latitude of Laramie the formation includes many beds of sandstone, and these increase in thickness to the south and west, until near the Colorado line very little limestone remains. Much of this sandstone also is of red color—a feature which becomes even more prominent in Colorado, where along the east side of the Front range the formation consists mostly of red beds and becomes the lower Wyoming, or Fountain formation, of previous publications.

Casper to La Bonte creek.—The limestones and sandstones of Casper mountain and the ranges extending east are from 350 to 700 feet thick and lie unconformably on the pre-Cambrian. There is usually a basal sandstone or quartzite, often conglomeratic, generally from 60 to 100 feet thick to the west, but thinning to the east, so that in the slopes west and south of Douglas the limestones lie very near or directly on the schists and granite. The limestone is from 200 to 500 feet thick, and at the top of the formation is a hard, gray, massive sandstone from 50 to 60 feet thick, which doubtless represents the Tensleep sandstone of the Bighorn and Wind River ranges. This tripartite character is shown in lower cut of plate 25. The limestones are mostly of light gray color, massively bedded and hard, and some of them contain chert. Red shales and thin sandstone members are included locally. Extensive exposures occur in Muddy, Deer, Boxelder, and La Prele canyons, the latter showing a fine arch and the upper sandstone member constituting the well

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Wind River mountains and eastward.—Near Sage creek, on the north slope of Wind River mountains, the Embar formation presents the following beds:

Section of Embar Formation West of Fort Washakie, Wyoming

	Feet
Shaly limestone	2
Yellow shale	25
Sandstone	4
Yellow shale	75
Limestone, cherty in upper and lower parts; many fossils..	30
Yellow shale	40
Limestone (on Tensleep sandstone)........................	10
Total..	186

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CASPER FORMATION, RED BUTTES, WYOMING

The monument is red sandstone; height, about 30 feet

bright red sandstone underlain by gray sandstones over 100 feet thick. At the big spring east of Laramie there is locally a 6-foot bed of pure limestone at top of Casper formation which is extensively quarried. In the southeastern portion of Laramie basin the limestones become a deeper purple, more sandy and thinner bedded than they are farther north. A short distance south of Laramie red shale and arkosic sandstone are the prevailing rocks, and the limestones which do not disappear persist as thin beds in the arkose to the Colorado line. In the slopes south of Laramie there is, about 350 feet below the top of the formation, a sandstone member about 200 feet thick, divided into three ledges by thin limestone beds. This sandstone is fine-grained, massive, cross-bedded, light red to salmon colored and weathers into fantastic forms or monuments, some features of which are shown in plate 26. The diminution in number and thickness of the limestones to the southwest, as well as the thinning of the formation in that direction, are shown in the following sections:

Partial Section of Red Beds in the Vicinity of Pulpit Rock, on Sand Creek, 9 Miles East of Red Mountain, at Colorado State Line

		Feet
	Wavy, gypsiferous limestone } Chugwater	2
	Red shales with aragonite } Chugwater	100±
	Wavy, gypsiferous limestone (Forelle ?)	4
Casper	Light buff sandstones and shales	100±
Casper	Flaggy to massive, light colored sandstone	30
Casper	Limestone (thins out)	1
Casper	Massive, fine-grained, red, monumental sandstone	40
Casper	Shale, arkosic sandstone, and conglomerate	40
Casper	Heavy, blocky limestone; forms slope in this vicinity	5
Casper	Sandstone, arkose sands, and conglomerates	170
Casper	Sandstone	5
Casper	Arkosic sandstones and conglomerates	80
Casper	Limestone	2
Casper	Arkosic sandstones and conglomerates	25
	Total	604

Section of Red Beds at Red Mountain (condensed from W. C. Knight's Section)[a]

		Feet
Chugwater	Red sandstone and shale	675
Chugwater	Gray, wavy quartzite (gypsiferous limestone ?)	5
Chugwater	Red shale and sandstone	100
Chugwater	Red clay and gypsum, with aragonite crystals	20
Chugwater	Solid gypsum	50

[a] Laramie Plains red beds and their age. Journal of Geology, vol. 10, 1902, pp. 418-419.

		Feet
Forelle......	Fossiliferous rock	4
Casper.....	Gray sandstone	20
	Red sandstones	15
	Interval not over................................	50
	Red sandstone	152
	White to red, shaly sandstone......................	96
	Reddish, fine-grained, "monument" sandstone.........	52
	Shelly, drab limestone..............................	2¼
	Red sandstones and conglomerates..................	124
	Red to gray bedded sandstone, with plants...........	22
	Light to red, coarse sandstone and conglomerate......	166
	Drab, calcareous sandstone.........................	1½
	Light gray to red, coarse sandstone and conglomerate.	86
	Granite.	
	Total....................................	1,640¾

The lower portion of this section was measured on Sand creek near the Pulpit rock.

Another section, by Mr Siebenthal, is as follows:

Section of Casper Formation on Red Mountain

	Feet
Fossiliferous impure limestone (Forelle—overlain by 67 feet of gypsum at base of Chugwater formation)............	1
Buff shale and calcareous sandstone....................	9
Massive, light sandstone................................	50
White, arenaceous shale and a little soft sandstone.......	55
White, soft, massive sandstone..........................	18
White, arenaceous shale................................	20
Red, arenaceous shales and thin, flaggy, red sandstone....	90
Pink to white, massive sandstone, some arkose............	39
Red shale	6
Sandstone	4
Red shale, sandstone and shale, limestone nodule horizon..	161
Concealed red beds, shales, sandstones, and arkose........	155
Granite.	
Total....................................	608

In these sections only two limestones remain, and they are inconstant and impure.

East slope of Laramie mountains.—In the eastern front ridge in Wyoming limestones predominate in the Casper formation to the north, but much reddish sandstone is also included. Farther south and in Colorado the formation changes into red sandstones, constituting the "lower

red beds," or Fountain formation. The following section shows the components at the Colorado state line. It was made by Mr Siebenthal:

Section of Casper Formation along Colorado-Wyoming Line

	Feet
Bright red sandstone and shale (Chugwater).	
Flaggy buff dolomite	8
Blocky limestone	4
Red shaly sandstone	11
Alternating shaly limestone and clay	11
Massive pink dolomite; shows bedding when weathered	35
Salmon-colored sandstone	5
Limestone	2
Red sandstone and shale	53
Limestone	10
Red shale ?	10
Limestone	25
Red sandstone	15
Massive limestone	10
Concealed	110
Buff to blue limestone	35
Red, massive sandstone	80
Limestone	10
Buff to red, massive sandstone	70
Bluish to purplish limestone	34
Salmon-colored, massive sandstone, fine-grained	25
Dark brown, coarse-grained sandstone	2
Purplish lumpy limestone	4
Buff arkose conglomerate	6
Dark brown, coarse sandstone	6
Massive, shaly, purplish limestone	12
Limey sandstone and sandy limestone	5
Concealed, shale ?	15
Purplish sandstone and arkose, with limestone cement and lenses of limestone	4
Concealed strata to granite	180
Total	797

On Duck creek, 4 miles north of the above section, all of the Casper formation is exposed excepting an unknown but probably small amount of the upper beds. The following section was measured by Mr Siebenthal at this locality:

Partial Section of Casper Formation on Duck Creek, 4 Miles North of Colorado-Wyoming State Line

	Feet
Tertiary.	
Massive dolomite	10
Concealed	28
Pink sandstone	4
Concealed	47
Pink sandstone	8
White limestone	10
Concealed	10
Red sandstone	5
Massive limestone	15
Concealed shale, perhaps with lenses of limestone	95
Massive limestone	15
Concealed	25
Purple limestone	25
Flaggy red sandstone	17
Purple limestone	12
Shale	19
Limestone	25
Shale	3
Limestone	4
Shale	3
Purple limestone	5
Shale	8
Purple limestone	10
Shale (?)	50
Limestone	3
Shale	8
Purple sandy limestone	6
Shale (?)	58
Blue to purple limestone	2
Concealed, probably red shale and sandstone	180±
Gneiss and schist.	
Total	720

The Casper formation crosses the Union Pacific railroad just east of Granite Canyon station, but owing to extensive overlap of the Tertiary the exposures are not complete. In the isolated butte a mile northeast of the railroad the following beds appear, probably representing very nearly the entire thickness of the formation. They were measured by Mr Siebenthal:

Partial Section of Casper Formation a Mile Northeast of Granite Canyon Station

	Feet
White limestone	10
Red sandstone	40±
Red or purplish limestone	10±
Red sandstone	30±
Red limestone	10
Red arenaceous shale	30
White dolomitic limestone	10
Red shale, grading into limestone toward top	64
White dolomitic limestone	70
Red sandstone	18
White limestone	4
Red sandstone	19
Red shale	10
Shelly monumental red sandstone	10
Red and white limestone	47
Massive white limestone	65–95
Red shale	45–15
Limestone	43
Shale	17
Limestone mostly; some shale	70
Red massive sandstone	23
Red shelly limestone	85
White massive limestone	12
Red shelly limestone	10
Concealed, probably shale, to granite	43
Total	795

Section of Casper Formation in South End of Table Mountain, on North Fork of Crow Creek

	Feet
Massive white limestone	30
Purple limy shale and flaggy limestone	50
Limestone, flaggy	10
Sandy shaly limestone	10
Purple limestone	40
Heavy-bedded white limestone	40
Red, cross-bedded, massive sandstone	20
White limestone	1¼
Red to purple limestone	6
Red sandstone	36
Limestone	2
Hard, purple, limy sandstone	20
Soft red sandstone	20
Light purple limestone	6
Red limestone	50

	Feet
White limestone	10
Concealed, debris slope	150
Arkose conglomerate and red sandstone	24
Shale	17
Red flaggy sandstone	15
Parti-colored shales	10
Calcareous sandstone on schists	4
Total	571¼

On Lodgepole creek there is gradual increase in the proportion of limestone in the Casper formation while the total thickness decreases to 500 feet or less. On Horse creek the basal beds are sandy limestones and near the middle of the section is a 30-foot bed of reddish brown sandstone. The main body of limestone is overlain by a 40-foot bed of reddish brown, soft sandstone, and then follows a succession of 5 feet of massive, white, hard limestone and 20 feet of very pale red sandstone. The latter is succeeded by red shales and sandstones of the lower part of the Chugwater formation. The Casper formation in this region is shown in plate 25.

The following section was measured for me by Dr W. S. Tangier Smith:

Section of Casper Formation at Iron Mountain Station, Wyoming

	Feet
Limestone	5
Reddish sandstone	15
Limestone	40
Red sandstone	25
Massive limestone	135
Reddish quartzitic sandstone	12
Massive gray limestone	40
Quartzitic red sandstone and conglomerate	25
Compact limestone	25
Red coarse-grained sandstone and medium coarse conglomerate	25
Conglomerate, quartzitic, light colored	10
Granite.	
Total	357

Fossils.—The Casper formation has yielded but few fossils. In the 24-foot bed of limestone in Gilmore canyon, 8 miles southeast of Laramie, a single *Spirifer cameratus* was found. The 8-foot bed of limestone 270 feet above yielded the following species, determined by Dr G. H. Girty:

Derbia ? sp.	*Euphemus* sp.
Aviculipecten occidentalis.	*Bellerophon crassus.*
Aviculipecten 2 sp.	*Soleniscus hallanus* ?
Myalina permiana ?	*Murchisonia* aff. *M. terrebra.*
Pleurophorus ? sp.	*Tainoceras occidentale.*
Schizodus sp.	*Nautilus* sp.
Schizodus meekanus.	*Orthoceras* sp.
Patellostium montfortiannum.	*Ammonoid indet.*

Doctor Girty regards this fauna as very closely related to that of the upper part of the Pennsylvanian division in the Kansas section.

There were found in limestones in the middle of the formation, on slopes of Laramie mountain 20 miles north of Laramie, *Productus semireticulatus, P. cora. Archæocidaris* sp., and *Pinna* sp.; in the upper limestone 2 miles east of Laramie, *Bellerophon* sp.; in the lowest limestone, on the mountain crest 6 miles east of Laramie, *Mekella striaticostata, Spirifer cameratus,* ? and *Bellerophon* sp.; in the upper limestone 9 miles southeast of Laramie, abundant *Orthotetes* sp., and in the lower limestones, at head of Gilmore canyon, 9 miles southeast of Laramie, *Spirifer cameratus.* These were determined by Dr G. H. Girty, and are all Pennsylvanian.

Mr Arnold Hague, of the 40th Parallel Survey,[10] reported distinctive Pennsylvanian fossils from localities on Sybille creek, Cheyenne pass, and at a point 5 miles northwest of Sherman. The two latter are southeast of Laramie. At the first place the fossils occurred in 200 to 300 feet of limestones about 200 feet above the granite, the second locality was at about the same horizon, and the third was the basal limestone lying on a thin mass of lower red sandstones.

In the lower portion of the limestone of the Casper formation, in Twin Squaw butte, 17 miles northeast of Iron Mountain station, the following species were obtained: *Chonetes mesolobus, Productus cora, Squamularia perplexa, Seminula* ? sp., and some ostracods.

Hayden[11] reported *Athyris subtilita* from cherty limestone of the Casper formation on Boxelder creek, and *Hemipronites crassus, Productus nodosus,* and *Myalina perattenuata* from the blue limestone over very cherty limestone on La Prele creek. *Spirifer centronatus* and *Straparollus utahensis,* obtained from cherty limestone on red shale at base of Casper formation, 7 miles northwest of Marshall, are Mississippian forms probably indicating basal Amsden beds, which belong in that division.

[10] Geological Survey of the 40th Parallel, vol. 2, Descriptive Geology, pp. 76-77.

[11] Fourth Annual Report, U. S. Geological Survey of the Territories, part 1, 1871, pp. 23-25.

Correlation.—From the general composition and stratigraphic relations of the Casper formation, it is believed to represent the Amsden and Tensleep formations of the Bighorn and Wind River regions, the Minnelusa formation of the Black hills, or the Hartville limestone of the Hartville uplift, but the precise stratigraphic equivalency and limits are not apparent. The persistent red shale, which appears in the basal portion of the formation in the northwestern portion of Albany county and rises still higher to the northwestward, doubtless represents the basal member of the Amsden formation, and if this is the case the underlying limestone is Madison, which can be separated by future detailed field work in Carbon and Natrona counties and perhaps also in Converse county. Although the upper member of the Casper formation is a massive buff to white sandstone, supposed to represent the Tensleep sandstone, this is not everywhere separable from the underlying members, notably in the region south of the latitude of Laramie. As the lower portion of the Amsden formation is Mississippian, the lower part of the Casper formation also extends into that division, at least in the region north of the canyon of Laramie river through Laramie mountains. As there is overlap of the higher beds to the south, it is probable that at the latitude of Laramie, and even for some distance farther north, the Casper formation is entirely of Pennsylvanian age.

FORELLE LIMESTONE AND SATANKA SHALE

In the vicinity of Laramie the limestones and sandstones of Casper formation are succeeded by about 200 to 232 feet of red shale capped by a thin but conspicuous and persistent bed of limestone. For these the names of Forelle limestone and Satanka shale are proposed, from stations on the railroad a few miles south of Laramie.

The Forelle limestone outcrops along the west slope of Laramie mountains from about 5 miles south of Red Buttes to Howell, and apparently also at Boswell spring, 23 miles east of Medicine Bow. It varies in thickness from 4 to 20 feet, and gives rise to a low ridge separated from the main slope by a shallow valley excavated in 200 feet or more of Satanka red shale which underlies the limestone. The outcrop is a short distance west of the great springs 2 miles east of Laramie, and it crosses the railroad at Forelle and Red Buttes. In places the limestone is fossiliferous. Locally it becomes gypsiferous and southeast of Laramie a 10-foot bed of gypsum occurs in the red shales a short distance below it. In the railroad cut just south of Forelle, where the limestone is well exposed, it is heavily bedded, quite pure, and nearly 20 feet thick. To the south, near Red Buttes and beyond, the rock becomes gypsiferous, varies from

massive to thinly laminated in structure, is locally brecciated, and it splits into several beds, some of which give place to shale. At the plaster mill south of Red Buttes the underlying Satanka red shales contain two beds of gypsum about 25 feet apart. One bed 15 feet thick is now worked, and another one, 10 feet thick, was formerly worked. The limestone is hidden by alluvium in part of the region southwest of Red Buttes, but an outcrop occurs on Antelope creek, halfway to Red mountain, which yields the distinctive fossil, *Myalina perattenuatus,* that occurs north of Laramie. It outcrops again farther southwest, on the west side of Sand creek and in the Red Mountain region, where there are no underlying Satanka red shales and the limestone lies directly on Casper sandstones. Apparently it is this bed that immediately underlies the 67-foot gypsum bed in Red mountain and yields the numerous fossils discovered by Professor W. C. Knight.[12] On the northwest slopes of Red mountain this limestone appears under the gypsum and, although thin, yields distinctive fossils.

The Forelle limestone contains fossils in small number throughout its course. On the east side of Laramie basin the only species identified is *Myalina perattenuata,* and this appears to be characteristic. The supposed Forelle limestone, lying just below the gypsum, on the northwest slope of Red mountain, afforded *Aviculipecten occidentalis, Myalina perattenuata, Allerisma terminals,* and *Schizodus compressus.* In the section on the east side of Red mountain this limestone consists mostly of casts and impressions of fossils which were discovered by Professor Knight in 1902.[13] According to Doctor Girty, they comprise the following:

Solenomya n. sp.	*Pleurophorus* aff. *P. taffi.*
Deltopecten manzanieus.	*Dentalium canna.*
Deltopenten corevanus ?	*Orthonema* ? sp.
Schizodus meekanus.	*Mevalima perattenuata.*

This fauna is late Pennsylvanian or possibly equivalent to the lowest limestones in the so-called Permian of Kansas.

The Forelle limestone is separated on account of the Carboniferous fossils which it contains. If it were not for this evidence, the limestone and underlying Satanka shale might be regarded as a portion of the Chugwater formation, for near Laramie and Red Buttes the stratigraphic succession is strongly suggestive of Minnekahta limestone lying on Opeche red shale. The latter limestone occurs on the east side of Laramie mountains and in the Black hills, and contains "Permian" fossils in the sense

[13] Loc. cit., p. 419.

in which the term Permian is used in the Mississippi valley. The Forelle limestone may possibly represent the Embar formation.

PERMIAN-TRIASSIC ?

CHUGWATER RED BEDS

General relations.—The Chugwater formation ranges in thickness from 900 to 1,200 feet and consists of sandy shales or soft, massive sandstones, nearly all of bright red color. Gypsum deposits occur in most places. There are extensive exposures along the lower northeastern slope of the Wind River mountains, in the Owl Creek, Bridger, and Rattlesnake uplifts, in the flexures south of Casper and Douglas, about Alcova, in the Shirley and Freezeout hills, in the anticlines north and east of Medicine Bow, and along the east side and across the south end of Laramie basin. It appears also at intervals along the east slope of Laramie mountains. In the greater part of the south-central Wyoming region the Chugwater formation lies on Tensleep sandstone, but in the southern end of the Laramie basin it lies on red beds of the Casper formation, from which in places it is not easily separated.

Wind River uplift.—The Chugwater formation outcrops along the northeast slope of the Wind River uplift, excepting for a short distance near Dinwoody lake, where the Tertiary overlaps across to the older rocks. It also appears in three areas along the anticline which passes east of Fort Washakie, Lander, and Dallas. In this region the formation is about 1,250 feet thick, and consists mostly of red shales and red sandstones. The upper beds are pinkish and contain much gypsum and limestone. Some of the sandstone beds are 50 feet thick and in part of gray color. On Sage creek, west of Fort Washakie, the formation is the same as at Lander, but has 4 feet of dolomite in the middle. South of Circle the formation has at top a ledge of rusty sandstone for a short distance. Other ledges of sandstone occur below.

Owl Creek uplift.—The Chugwater outcrops extensively along both sides of the Owl Creek uplift, and it appears again in Thermopolis anticline. Exposures of considerable width extend along the south side from North fork of Muddy creek to Black mountain. The thickness averages 800 feet, with but little local variation, and the rocks do not vary greatly in character in different portions of the uplift. Toward the top and bottom red shales predominate, while in the middle soft sandstones and alternations of sandstones and shales are the principal features. Near the base there is usually a thin bed of purplish gray limestone from 18 inches to 3 feet thick, and in some portions of the area two such limestones

appear. A widespread sheet of limestone about 2 feet thick lies from 100 to 150 feet below the top of the formation, and on the east bank of Bighorn river, 3 miles north of Thermopolis, it yielded many fossils. At a few localities, especially near the head of Mud creek and at the south end of Bighorn canyon, the upper portion of the formation contains a number of beds of gray to buff sandstone. To the west there is a prominent bed of orange-colored, massive sandstone overlain by a thick bed of gypsum, the top of which is about 100 feet below the top of the formation. This gypsum bed is 30 feet thick south of Embar and on Red creek southeast of Thermopolis and 40 feet in extensive exposures on Muddy creek. Near the middle of the formation there is usually a massive bed of pale red sandstone of fine, uniform grain.

Rattlesnake mountains.—The Chugwater outcrop extends for about 13 miles along the northeast slope of Rattlesnake mountain. The formation is about 1,200 feet thick. At the top are 200 feet of red shales and sandstones lying on an 8-foot bed of limestone which caps a red wall. Some thin limestone beds occur in the top member and also toward the base of the underlying red sandstones and shale. No large deposits of gypsum appear.

Casper-Douglas-Medicine Bow region.—In the vicinity of Casper mountain and the other ridges at the north end of the Laramie uplift the Chugwater formation presents its usual features, but near Douglas and Big Muddy the Minnekahta limestone of the Black Hills and Hartville region appears in its lower part with thickness of 20 to 25 feet. The underlying red shales (Opeche) are 80 feet thick and the overlying red sandstones and shales are 450 feet or more. Exposures are extensive on Muddy creek and its branches in the syncline south of Casper mountain, and in the high red wall surrounding the Haystack range. The Minnekahta limestone is characteristically thin-bedded and of purplish tint. Eighty feet higher is a 15-foot bed of cherty limestone, and near the top of the formation is a 20-foot limestone member, which gives rise to a prominent "wall" in the steep dipping beds on Muddy creek at the east end of Casper mountain. Overlying this limestone are 20 feet or more of white to red sandstone; then a few feet of buff sandstones and shale with an 8-foot bed of gypsum. East of Muddy creek the outcrops are continuous to the Tertiary overlap south of Glen Rock. The formation appears again for a short distance on La Prele creek just below the Natural bridge. In this region 20 feet of Minnekahta limestone lie on 80 feet of red shale (Opeche) which rests on Tensleep sandstone. East of La Prele creek the red beds are covered by Chadron formation, but they reappear south of Douglas and extend up the valleys of Wagonhound and

La Bonte creeks, where the formation contains considerable gypsum near its base. Extensive exposures occur in North Platte river, in the big bend 7 miles due south of Douglas. In the axis of the anticline in this bend the Minnekahta is bared, lying on red shale of which 50 feet are exposed. Here the limestone outcrops in massive ledges, but it is thin-bedded. Its upper part is mottled dark gray, but at the top are 5 feet of more massive light colored limestone. The basal red shales, 80 feet thick, are exposed in the gorge of Wagonhound creek 9 miles south-southwest of Douglas, lying on dark Tensleep sandstone at top of Casper formation.

Southwest of Casper the Chugwater formation consists of the following beds:

Section of Chugwater Formation, 1¼ Miles Southwest of Casper, Wyoming

	Feet
Massive, pale red, fine sandstone; some red shale.........	60
Hard, slabby, purplish limestone........................	15–25
Red sandstone and red sandy shale......................	500
Thin-bedded buff limestone..............................	2
Red sandy shale	40
Limestone, slabby below, massive and hard at top.........	15
Red shale (on Tensleep sandstone)......................	30

The hard limestone member near the top of the formation is a conspicuous feature at the west end and south side of Casper mountain, about Alcova, and in the Shirley and Freezeout hills. It usually caps a red wall where dips are low or causes a ridge, as shown in plate 27, where dips are steeper. Near Freeland it is 20 feet thick and separated from basal gray sandstone of Sundance formation by 60 feet of red, massive sandstone. North of Difficulty it is 8 feet thick, but in northeast portion of Freezeout hills it is only 4 feet thick and lies on 10 feet of gray sandstone. North of the mouth of Medicine Bow creek there are three limestones in the upper part of the formation. A short distance farther west there is only one upper limestone, which is 8 feet thick and lies between 250 feet of red shale above and 900 feet of red beds below. The latter include 3 thin limestone beds near their base. In the Freezeout hills these basal limestones give place to a 30-foot bed of gypsum. In the vicinity of Alcova the following section is typical:

Section of Chugwater Formation Southeast of Alcova, Wyoming

	Feet
Red sandstone	40
Red shale and slabby sandstone; some buff..............	125
Limestone, hard, gray; caps "Red wall".................	20
Red shale	15
Red sandstone	10
Red sandy shales and sandstones........................	450

FIGURE 1.—CHURCH ROCK

An outlier of red sandstone of the Chugwater formation in the southern portion of the Laramie Basin, Wyoming

FIGURE 2 —LIMESTONE RIDGE IN UPPER PART OF CHUGWATER RED BEDS, SOUTHWEST OF CASPER

Ridge of Cloverly sandstone to the left, hills of Benton shale to the right. Looking west

MEMBERS OF THE CHUGWATER FORMATION

	Feet
Sandy shales and sandstones, mostly red; gray sandy beds near base; much gypsum; chert nodules in middle	100
Red shale	60
Limestone, gray, moderately massive	8
Red sandy shales and sandstones (on Tensleep sandstone)	80
Total	908

In the slopes 3 miles north of Medicine Bow the thickness is about 1,300 feet. At the top are about 10 feet of red shales, followed in descending order by 20 feet of gray, slabby sandstone, 100 feet of red, sandy shales, 8 feet of gray, slabby sandstone, 30 feet of red shale, 2 feet of gray sandstone, slabby and ripple-marked, 3 feet of red shales, 8 feet of soft gray sandstone, and then a thick succession of red sandy shales and soft red sandstones. Toward the base are several members of thin-bedded sandstone 5 feet and less in thickness.

At Boswell spring, 23 miles east of Medicine Bow, the red beds include a 3-foot bed of impure pink limestone which may belong either in the lower part of the Chugwater formation or represent the Forelle limestone. It lies on red, slabby sandstone merging down into red shale, which underlies the valley extending to the slopes of sandstone (Tensleep). A similar limestone 4 feet thick appears near the head of Sybille creek, where it is separated from the Tensleep sandstone by 125 feet of red shale.

Laramie basin.—Near Laramie and to the south and southwest the Chugwater formation consists mostly of red shales and fine-grained, red sandstones, with a subordinate amount of lighter colored sandstones, thin beds of limestone, and deposits of gypsum. The latter are notably thick and prominent in the Red Mountain neighborhood. The fine-grained, massive sandstones weather with rounded outlines, especially where the beds are horizontal, and in places they rise in "monuments," one of which is shown in plate 27. The following complete section of the formation was measured by Mr Siebenthal in the north face of Red mountain:

Section of Chugwater Formation in Red Mountain, Wyoming

	Feet
Morrison shales and limestone.	
Light sandstone	12
Terra cotta to blue shale	20
Soft sandstone or sandy shale	10
Terra cotta shale	17
Light buff, soft, massive sandstone	30
Terra cotta, blue, and green shales	65
Light shales	22
Heavy, flaggy, light to buff sandstone and light shales	30

	Feet
Pink, massive, fine-grained sandstones	24
Reddish salmon-colored sandy shales	35
White, flaggy sandstone and red shales	45
Massive, cross-bedded, fine-grained salmon sandstone	15
Flaggy, white sandstone and reddish shales	20
Massive, cross-bedded, fine-grained salmon sandstone	65
Typical red shales and red flaggy sandstone	450
Red gypsum, nearly pure	6
Red shale	35
Gypsum	3
Red shale	10
Gypsum	4
Red shale	55
Fine, banded, wavy, gypsiferous limestone	5
Red, sandy shale (with aragonite crystals)	88
Gypsum, pure, massive	67
Total	1,133

The upper limit of the formation is placed arbitrarily at the base of a blue shale which lies below the lowest limestone containing Morrison fresh-water fossils. This includes in the upper part of the Chugwater an alternation of about 200 feet of terra cotta, blue, and buff shales and light colored sandstones, which are not typical and are absent in the region northeast, but they appear more likely to belong in the Chugwater than in the Morrison formation. The gypsiferous member at the base of the Chugwater formation is 273 feet thick in this section and consists of alternations of gypsum, gypsiferous limestone, and red shales, and at the base a massive bed of pure gypsum 67 feet thick lying on supposed Forelle limestone. In the red clay 20 feet above the gypsum there are numerous crystals of aragonite which, according to Knight, are pseudomorphic after hanksite. Above the gypsiferous measures are 450 feet of typical red shales and flaggy red sandstones, followed by 378 feet of massive, fine-grained, salmon colored sandstones, with a minor proportion of red shale. These sandstones weather into "monuments" and walls similar to those formed by the "monument" sandstones of the Casper formation. On Sand creek near North Park road, where the gypsum is only from 2 to 4 feet thick, it is associated with and sometimes replaced by gypsiferous limestone lying on wavy-bedded gypsiferous limestone believed to represent the Forelle limestone. Aragonite crystals occur in the overlying red shales. Six miles southwest of Red Buttes the gypsum appears to overlie wavy, gypsiferous limestone, which can be traced northward with certainty into the Forelle limestone which crosses the railroad at Forelle. Northwest of that place a well 333 feet deep is reported to be in red beds and

gypsum overlying Forelle limestone. This evidence throws light on the probable continuity of the Forelle limestone across the south end of Laramie basin.

In the Centennial valley the gypsum measures are represented by a thin, gypsiferous limestone bed, separated from the supposed Forelle limestone by red shales. They are overlain by alternations of red shales and soft, red sandstones. The upper part of the formation includes the "monument" sandstones, as in the region southeast.

East side of Laramie mountains.—In the foothills of the western part of Laramie county the Chugwater formation is about 900 feet thick. It comprises 375 feet of red sandy shale and soft red sandstones, 50 feet of gypsiferous beds, thin limestones, and red shales, and at the top 450 to 500 feet of red sandstone and shale. On the south prong of Horse creek the formation is 1,000 feet thick. About 100 feet above its base are 15 feet of slabby limestone resembling the Minnekahta limestone. On South fork of Horse creek there is a 50-foot bed of massive gray sandstone at the top of the formation—a feature often seen in Colorado; possibly this member may belong to the Sundance formation. In Horse Creek canyon, where the beds are vertical, the basal red shale and thin-bedded sandstone thicken to 260 feet. Next above is a 20-foot bed of dolomitic limestone which gives rise to a small but prominent ridge extending some distance north. It is massive above and thin-bedded and purplish below. Next are 70 feet of red shale, 4 feet or more of porous dolomite, 100 feet of red shale, 5 feet of fine-grained, massive, pure white limestone and 660 feet of red shales capped by 40 feet of reddish gray sandstone. Just south of North fork of Horse creek the formation has a limestone member about 100 feet above its base, probably a continuation of the 20-foot bed on the main creek, and the underlying red shale member is less thick.

About Iron Mountain station the formation is between 700 and 800 feet thick in a section measured in beds dipping from 43 to 78 degrees. The rocks are mostly red sandy shales grading into red sandstones, most of which contain considerable clay. Near the middle of the formation are two thin layers of limestone and at the base the following beds:

Section of Lower Beds of Chugwater Formation just North of Iron Mountain Station, Wyoming

	Feet
Brownish red, soft, massive sandstone (under thick mass of red beds)	10
Limestone, white, massive	5
Brownish red sandstone, moderately soft, massive	40
Thin-bedded limestone	6
Brownish red sandstone	3
Limestone with Pennsylvanian fossils	Many

These brownish red sandstones with limestone layers in the basal series may possibly represent the Tensleep sandstone, but if so the Minnekahta limestone is absent in overlying red beds. The top member of the Chugwater red beds here is a massive bed of pale red sandstone.

Fossils and age.—Fossils found at various horizons in limestones in the Chugwater red beds do not afford conclusive evidence as to age. Those in the lower limestones in the Bighorn mountains and other uplifts are believed to be "Permian" in the sense in which the term is used in the Mississippi valley. Many fossils occur in the limestone 150 feet below the top of the formation, on the east bank of Bighorn river, 3 miles below Thermopolis. According to Dr G. H. Girty, the principal species is *Natica lelia,* usually considered diagnostic of the Triassic, but probably it is older. *Bakewellia* and probably *Phleurophorus* may also be present, and an aviculipecten occurs, resembling *A. curticardinalis,* which is characteristic of the Permo-Carboniferous of Utah. Doctor Girty is inclined to correlate the fauna with the Permo-Carboniferous of the Wasatch Mountain section. The 150 feet of red shales and sandstones which overlie this limestone may possibly represent part of the Triassic. In the lower portion of the Chugwater formation, 10 miles southwest of Casper, a cast of *Schisodus wheeleri* was found. This form is usually regarded as Pennsylvanian.

Jurassic System

SUNDANCE FORMATION

General relations.—The Sundance formation occupies a large area in central Wyoming, but it is absent in the Laramie basin south of Rock river. In Wind River basin it is mostly covered by Tertiary, but it outcrops extensively near Fort Washakie, Lander, and Dallas. It appears along both flanks of Owl Creek mountains, on the north slope of Rattlesnake mountains, in southeastern Natrona county, in northeastern Carbon county, in the flexures south of Douglas and east and northeast of Medicine Bow, and along the east side of Laramie Mountains from Iron Mountain station to Crow creek. Although there is a long time interval between the Sundance and Chugwater formations, marked erosional unconformity is rare and in places it is difficult to draw the line between them. This is probably because the first sediments of the upper formation were derived from the one below. The upper limits are similarly ill-defined. There is no discordance in dips of underlying or overlying formations.

Owl Creek uplift.—In the Owl Creek Mountain region the Sundance formation consists of about 200 feet of soft gray sandstones and green

shales with conspicuous hard layers. On the north slope the outcrop extends from a point 4 miles west of Embar nearly to Deranch and also around the Thermopolis anticline. On the south side it extends westward from North Fork of Muddy creek to the base of Black mountain, and it also appears in small exposures near longitude 108° 30′, at the upper end of Bighorn canyon and in the two uplifts between Dry and Muddy creeks, near longitude 109°. The local stratigraphy varies somewhat. At the base are sandstones; the middle and upper beds are mainly shales, and there is more or less sandstone for about 40 feet at the top. The shales are greenish or dark gray and contain limestone in concretions and thin layers, often highly fossiliferous. In the western portion of the uplift one of the upper sandstone beds is so hard that it causes high, narrow ridges, which are especially prominent in the divide west of Dry creek. Near Embar and eastward a hard, dark gray sandstone, 12 feet thick, which makes a prominent ridge, is underlain by the basal member, 80 feet thick, of shale and soft greenish gray sandstones containing many *Gryphæa calceola.*

Section of Sundance Formation on Owl Creek, 7 Miles Northwest of Thermopolis, Wyoming

	Feet
Green, soft, sandy shales and hard greenish fossiliferous sandstone in alternating layers	70
Gray sandstone	4
Green sandy clay	20
Gray limy sandstone	2
Dark greenish gray, sandy clay, with many belemnites	40
Greenish gray sandstone, with occasional hard layers	30
Green sandy shale	20
Greenish gray sandstone, thin-bedded	4
Hard, buff, impure limestone, breaking into small rectangular blocks	2
Green sandy shale lying on "Red beds"	2
Total	194

The exposure at south end of Bighorn canyon is in the east bank of the river. Here there are about 250 feet of alternating layers of greenish gray sandy shale and dark gray, fossiliferous sandstone.

Wind River-Rattlesnake mountains.—Along the slope of Wind River mountains and in the uplifts passing east of Fort Washakie and Lander the Sundance formation is about 300 feet thick and consists of greenish gray shales and sandstones, with thin but prominent ledges of impure, highly fossiliferous limestone in their upper part. In the northern foot-

hills of the Rattlesnake mountains, where the thickness is about 300 feet. there are gray sandstones at the top, and part of the medial sandy shales are of pronounced reddish tint, as in the Black hills and some other districts in Wyoming.

Platte valley to Rock river.—The Sundance formation presents most of its usual features along the south side of Casper mountain, in Muddy Creek valley, and on Wagonhound creek and North Platte river south of Douglas. In the extensive exposures in the big bend of the river south of Douglas, there are 30 feet or more of massive gray sandstone overlain by 30 feet of pale greenish, sandy shale, 5 feet of soft, greenish, massive sandstone, 40 feet of soft sandstones of bright reddish tint, 15 feet of massive buff sandstone, and about 200 feet of green shale with 3 hard beds of fossiliferous limestone. In the high ridge southeast of Hammond the basal sandstone is 50 feet thick, massive, cross-bedded, moderately fine-grained, and of pale orange color. It is overlain by 50 feet of buff sandstone, mostly slabby; 30 feet of pale red, soft sandstone; 100 feet of shale with hard layers, and at the top a few feet of buff sandstone. The reddish sandstone continues for some distance to the south and west and is conspicuous 1½ miles east of Freeland, about Alcova, and along the south side of Shirley hills. In the Alcova region and southward the basal member is white, massive, cross-bedded sandstone in places 40 feet thick (see plate 28). West of Difficulty there is also a body of white sandstone in the overlying shale member, together with the usual hard, fossiliferous, limy layers. The following section is typical for the Alcova region:

Section of Sundance Formation near Alcova, Wyoming

	Feet
Green shale	65
Slabby, hard limestone	10
Green shale	10
Limestone	10
Green shale	75
Sandstone	5
Shale, part pink, part green	100
Sandstone, white (on Chugwater red beds)	25
Total	300

In the Freezeout hills and Rock River region the lower beds of the formation are predominantly sandy, while the upper part consists largely of green shales with hard, fossiliferous layers. In an extensive exposure east of Medicine Bow the strata are as follows:

FIGURE 1.—MASSIVE SANDSTONE AT BASE OF SUNDANCE FORMATION, SOUTH OF ALCOVA, WYOMING

The distant ridge is capped by Cloverly sandstone; red beds show in foreground

FIGURE 2.—CHUGWATER RED BEDS, SUNDANCE FORMATION, MORRISON SHALE, AND CLOVERLY SANDSTONE, SOUTH OF LANDER, WYOMING

Pool of petroleum in the foreground

Section of Sundance Formation in Como Ridge, 6 Miles East of Medicine Bow, Wyoming

	Feet
Morrison shales.	
Limestone and shale	15
Massive, disintegrated sandstone, in part shaly	10
Drab shale with few lumps of brown limestone	30
Buff, shaly sandstone	5
Yellow, sandy shale with belemnites	42
Buff, shaly sandstone	5
Yellow shale (lying on Chugwater red beds)	12
Total	119

Two miles north of Medicine Bow the lower half of the formation is a massive buff sandstone, with 8 feet of red shale about 100 feet above its base and a 2-foot bed of red shale a short distance higher.

A section in the eastern side of the Freezeout hills near Dyer's ranch, given by W. N. Logan,[14] is as follows:

Section of Sundance Formation in Freezeout Hills, Wyoming

No.		Feet
15.	Purplish clay with sandy inclusions (has sandy limestone layer near base filled with fossils)	40
14.	Greenish sandstone, thinly laminated	2–5
13.	Purplish, fossiliferous clay, with many lime nodules filled with fossils	20
12.	White, sandy clay, dinosaur remains	4
11.	Sandy clay with brown concretions; green sandstone layer near middle	6
10.	White, sandy limestone in thin layers (fossils)	½
9.	Sandy red clay	10
8.	White, fissile sandstone	6
7.	Shale, reddish, changing to purple	4
6.	White sandstone, moderately hard	½
2–5.	White sandstones, separated by 2 layers of red clay	1
1.	Red clay of Chugwater formation.	
	Total	94+

East of Laramie mountains.—The thin margin of the Sundance formation outcrops continuously along the eastern foothills from North fork of Horse creek to the southernmost prong of Horse creek and from the North to the South fork of Lodgepole creek. Small exposures appear on North and Middle forks of Crow creek. The rocks are mostly light buff sandstones, but some sandy shales appear. The average thickness is 40

[14] Kansas University Quarterly, vol. ix, 1900, pp. 111-112.

feet. In the first canyon south of South fork of Horse creek the rocks are mostly hard, buff sandstone, the upper third slabby and including some buff to greenish sandy shales. On South fork of Horse creek are 60 feet of slabby buff to gray sandstone, sandy shales, and grayish green shales lying on a 50-foot bed of massive gray sandstone, supposed to be the top of the Chugwater formation. South of Horse Creek canyon the lower 30 feet or more are greenish, sandy shale, above which are 10 feet of bright buff, soft sandstone extending to base of Morrison formation. Near Iron Mountain station there are two members: An upper one, 30 feet thick, of soft, slabby sandstone, gray at base and buff toward top, with ripple-marked layers and much intercalated shale; and a lower member, 50 feet thick, mostly of green to gray shale, with layers of soft, thin-bedded, greenish gray sandstone.

Fossils and equivalency.—The formation contains abundant fossils of middle to upper Jurassic age, and it is believed to be equivalent to the Sundance formation of the Black Hills region. The following are the principal fossils: *Belemnites densus, Gryphæa calceola,* var. *nebrascensis, Campectonites bellistriatus, Eumicrotis curta, Trigonia elegantissima, T. americana, T. conradi, T. montanensis,* and *Pentacrinus asteriscus.*

In Freezeout hills the following fossils are reported by W. N. Logan[15] in section given on page 441: Bed number 10, *Pseudomonotis curta;* bed number 12, remains of Ichthyosaurus and Plesiosaurus; bed number 13, abundant *Belemnites densus* throughout, and in the concretions *Pinna kingi, Pinna* sp. *Cardioceras cordiforme, Avicula beedei, Astarte packardi, Pentacrinus astericus, Tancredia bulbosa, T. magna, Lima lata, Goniomya montanaensis, Avicula mucronatus, Pleuromya subcompressa, Cardinia wyomingensis, Pseudomonotis curta, Belemnites densus* and *B. antus,* and also remains of plesiosaurs and ichthyosaurs; bed number 14, *Camptonectes bellistriatus, C. extenuatus, Ostrea densa,* and *O. strigilecula;* in a sandy limestone bed in base of bed number 15, *Pentacrinus astericus, Asterias dubium, Pseudomonotis curta, Avicula macronàtus,* and *Ostrea strigilecula.*

Cretaceous System

MORRISON FORMATION

General relations.—The Morrison formation extends throughout eastern and central Wyoming, presenting all the features which characterize it in the type locality in Colorado and in the Black hills and Bighorn mountains. It outcrops along the east side of Wind River mountains,

[15] Loc. cit., pp. 112-118.

along both sides of the Owl Creek uplift, the north side of Rattlesnake mountains, the anticlines south of Casper and Douglas, the Shirley and Freezeout hills, and the uplifts east of Medicine Bow and Rock Creek. It extends along the east side and across the south end of the Laramie basin and appears at intervals in the foothills on the east side of Laramie mountains. Two narrow zones of outcrop extend along both sides of Centennial valley, and the formation outcrops for 2 miles along the east slope of Jelm valley just east of Jelm. A small area is faulted to the surface east of Sheep mountain. In Laramie basin the Morrison formation lies unconformably on the Chugwater red beds, but elsewhere the Sundance formation intervenes.

The Morrison deposits are mainly hard clays or massive shales, varying in color from pale greenish to maroon and having a peculiar chalky appearance. The prevailing tint is pale olive green. Thin beds of drab limestone and occasional beds of light colored sandstone are included, and also in places masses, 2 inches or less in thickness, of olive green to dark green, brittle, siliceous rock of concretionary nature. Some typical exposures are shown in plates 28 and 29.

Wind River-Owl Creek region.—In the Wind River and Owl Creek uplifts the Morrison formation outcrops in a zone immediately adjoining the outcrop of the Sundance formation. Frequent exposures appear in the slopes of the ridges due to the Cloverly sandstone along both sides of the Owl Creek and Thermopolis uplifts, and in the Fort Washakie-Lander region, although the formation is often covered by talus on the slopes. In the Lander region the thickness is 225 feet, and the rocks are mainly pale green to maroon massive shales, with thin beds of sandstone. Ordinarily the upper portion is of buff tint and the lower portion partly maroon. About Fort Washakie the formation is 200 feet thick and has a 4-foot bed of sandstone near the middle. In the Owl Creek uplift the thickness varies from 100 to 250 feet in greater part, in general diminishing from east to west. The predominating material is the usual massive shale, or mixture of clay and fine sand, of pale greenish gray color, merging into deeper green, maroon, pink, and red. In the middle there are usually 50 feet or more of soft, fine-grained, greenish gray sandstone, which is well exhibited on the north slope of the anticline 4 miles northeast of Thermopolis. It is here overlain by 40 feet or more of sandy shale, in part of maroon tint; 10 feet of loosely consolidated conglomerate with pebbles mostly of a very dark color, and at the top 10 feet of highly carbonaceous, dirty buff shale. The basal beds here are reddish and greenish massive sandy shale. On North fork of Muddy creek the rock is mostly soft, fine-grained, white, very massive sandstone,

lying on a small amount of light colored shale of the usual character. Southeast of Embar this sandstone also predominates, merging downward into thin-bedded gray sandstones and more or less shale, which weathers to a buff color. In a small outcrop on east side of Bighorn river, just above the mouth of the canyon, the rock is mostly gray sandstone, but a thin bed of limestone is included. In extensive exposures on the east side of Red creek, 3 miles east of the summit of Black mountain, the formation is about 150 feet thick. At the top are soft, massive sandstones, mainly of buff color, but partly pink, lying on reddish and maroon clays. In the middle are 50 feet of red, sandy clays, with a few soft sandstone layers from 6 inches to a foot thick and some layers of purple clay. The lower 50 feet are massive, sandy clays of gray and dirty maroon tints in alternating bands lying on Sundance sandstone without evidence of structural discordance.

Casper-Douglas-Medicine Bow region.—The Morrison formation appears extensively in the slopes of the ridges of Cloverly sandstone from Poison Spider creek to head of Bates creek, about Alcova, south of Big Muddy station and Douglas, in the Haystack range, Freezeout and Shirley hills, in the uplifts north and east of Medicine Bow, and the long monocline on the east side of Little Medicine creek. In the east end of the Freezeout hills and in the Como ridge, 6 miles east of Medicine Bow, are the famous collecting grounds of dinosaur remains. The thickness varies from 200 to 300 feet. The material is the typical light colored, massive clay or mixture of fine sand and clay, with sandstone layers and occasional thin limestone beds. The clay is mostly pale greenish gray, but in all exposures portions are maroon and buff. Near Freeland the middle beds are distinctly red. In the vicinity of Alcova and southward there is a massive light colored sandstone at the base suggestive of the Unkpapa sandstone of the Black hills. It is 40 feet thick at the south end of Platte canyon 35 miles above Alcova. At this place and eastward nearly to Difficulty the thickness of the formation is 325 feet. The following section near Dyer's ranch by W. N. Logan[16] illustrates the principal features in the eastern end of the Freezeout hills, where, however, the stratigraphic limits are somewhat uncertain:

Section of Morrison Formation in Freezeout Hills, Wyoming

No.		Feet
24.	Grayish white sandstone (may be basal Cloverly)	50
23.	Drab clay with dinosaur remains	70
22.	Brown to bluish gray, sandy limestone with molluscan fossils	1

[16] Ibid., pp. 113-115.

	Feet
21. Bluish green clay with very small concretions, dinosaurs, and molluscs	30
20. Fissile, brownish sandstone; no fossils	4–5
19. Drab clay, brontosaurus remains	30–40
18. Sandstone, grayish to light brown, part cross-bedded, on 2½ feet of conglomerate; fossil wood and cycads	10–20
17. Purplish to greenish clay, with dinosaurs in upper part	60
16. Grayish white sandstone, fine-grained, part cross-bedded, moderately soft	10–125

Bed number 16 is only 10 feet thick at Dyer ranch, but increases to 125 feet a few miles south. It is separated from beds carrying Sundance fossils by 40 feet of purplish clays which may belong to the Morrison formation. A section in Como ridge is as follows:

Section of Morrison Formation in Como Ridge East of Medicine Bow, Wyoming

	Feet
White, massive sandstone, conglomeratic (Cloverly).	
Bluish to greenish shales	50
Limestone, lumpy	1
Bluish to olive green shales	30
Limestone, lumpy	1
Blue and red shale	120
Total	202

Laramie basin.—The Morrison formation outcrops on the west bank of Laramie river just below the bridge a mile northwest of Laramie. There are 3 feet of dark shale at base, then 20 feet of soft, massive light colored sandstone, and at top 10 feet of gray shale with several thin, slabby limestone layers, one of which is pebbly, and a thin layer of gray sandstone. In slopes 1½ to 2 miles south-southwest of Howell station are soft, massive buff sandstones overlain by typical gray and greenish gray massive shale or clay with thin limestone, cherty, and sandstone layers. One of the latter is 2 to 3 feet thick. At the top are very dark shales, which have been prospected for coal; these are overlain by coarse Cloverly sandstone.

Section of Morrison Formation on East Slope of Ridge West of Downey Soda Lakes, Wyoming

	Feet
Cloverly sandstones and shales.	
Drab to olive green shale	30
Soft, coarse-grained, disintegrated sandstone, with calcareous matrix containing teeth and bones	6
Drab to blue shale	15
Nodular limestone	1–2

	Feet
Blue shale	50
Limestone	2
Concealed, probably blue shale	30+
Total	135+

In Red mountain, where the formation is 128 feet thick, it consists mainly of pale bluish shale, which in the upper beds contains green nodular masses. Thirty-six feet above the base there is a 2-foot layer of limestone, and 88 feet above the base a 1-foot limestone layer containing fresh-water fossils. At the base are light colored sandstones and terra cotta and bluish shales, which may possibly represent the marine Jurassic, but, as they contain no fossils, they are provisionally classed as Chugwater.

East of Laramie mountains.—In the first canyon south of South fork of Horse creek the Morrison consists of pale green and maroon massive shale lying on 30 feet of light colored massive shale containing several layers of limestone, one 6 feet thick. On South fork of Horse creek the 6-foot limestone member is conspicuous, underlain by 20 feet of gray shale lying on a 1-foot limestone bed at supposed base of the formation. The total thickness here is about 200 feet, which appears to be the average amount, except on the southernmost prong of Horse creek, where it is less than 150 feet.

Fossils and age.—Many dinosaur remains have been obtained from the Morrison formation in southeastern Wyoming, notably from the extensive bone quarries near "Bone Cabin," in the northeastern portion of Freezeout hills, 15 miles north by west from Medicine Bow; on Rock creek east of Medicine Bow; on Sheep creek; on Como ridge, 6 miles east of Medicine Bow, and on Bone creek, 7 miles northeast of Medicine Bow. They comprise Brontosaurus, Morosaurus, Laosaurus, Camptosaurus, Dryosaurus, Ornitholestes, Diplodocus, Stegosaurus, and Allosaurus. Collections have also been made near Steamboat lake, southwest of Laramie. Bones have been found also at a point 2 miles east of Red mountain, west of Downey lake, east of Jelm, and also at several localities in Colorado a short distance south of the state line. In the drab, brittle, impure limestones in the shales are numerous remains of fresh-water molluscs, usually of very small size. Fossil algæ occur in the limestones along the east side of Laramie mountains. The following fossils were identified by Dr T. W. Stanton from west and southwest of Laramie: *Unio baileyi, Limnæa, Planorbis veternus, Volvata scabrida, Vorticifex stearnei, Viviparus,* ? and *Viviparus* n. sp. (very large); and from Como ridge: *Unio* sp., *Volvata scabrida.* and *Limnæa accelerata.* In the thin layer of brown sandy limestone in

FIGURE 1.—HOGBACK OF CLOVERLY CONGLOMERATE, 6 MILES NORTH OF FREELAND, WYOMING. LOOKING WEST

FIGURE 2. SUNDANCE AND MORRISON SHALES CAPPED BY CLOVERLY SANDSTONE, 6 MILES WEST OF DIFFICULTY POST OFFICE, WYOMING

CLOVERLY CONGLOMERATE AND SUNDANCE AND MORRISON SHALES, WYOMING

Freezeout hills (bed number 22 on page 444) Mr Logan reports *Unio knighti, U. willistoni, U. baileyi, Valvata leei,* and *Planorbis veternus.* The two latter also occur in bed number 21. Numerous cycads and fossil wood, together with a fragment of a hollow-boned dinosaur, are reported from bed 18 in the same section.

The dinosaur remains in the Morrison have been regarded as Jurassic, but some paleontologists believe that they are early Cretaceous. As the stratigraphic relations in some regions sustain this latter view, the formation is provisionally assigned to the Cretaceous.

CLOVERLY SANDSTONE

Occurrence and general character.—The Cloverly sandstone, at one time called the "Dakota sandstone," extends continuously through central Wyoming, usually giving rise to a hogback range on the slopes of the various uplifts (see plates 28 and 29). The outcrops extend along the sides of the Owl Creek and Bridger uplifts and the northeast side of the Wind River range, but in places it is covered by Tertiary. It appears again in the anticline extending from Dallas to beyond Fort Washakie; also on Conant and Muskrat creeks and along the north side of the Rattlesnake uplift, where it extends nearly to Oil City. It outcrops extensively about Alcova, along both sides of the uplift of the Freezeout hills, in the region southwest and south of Casper and Douglas, in the uplifts north and east of Medicine Bow, along the east side and south end of Laramie basin, in Centennial valley, and on the east side of Laramie mountains from Chugwater creek to Middle fork of Crow creek. A small outlier remains in the syncline near Jelm post-office. The principal rock is hard, coarse sandstone, nearly everywhere in two members, separated by gray and purplish clay. The lower sandstone is generally conglomeratic, at least in its lower portion. The formation averages 150 feet thick and lies on Morrison formation, with an erosional unconformity that is usual when coarse sandstone or conglomerate lies on shale or clay.

Owl Creek mountains.—In the Owl Creek Mountain uplift the thickness of the Cloverly formation ranges from 100 to 150 feet. The outcrop zone extends for many miles along the north side of the mountains and along their south side from the headwaters of North fork of Muddy creek to the Tertiary overlap south of Black mountain. Small exposures appear on the south side of the mountains, near longitude 108° 30′, and more extensive ones encircle the uplifts between Muddy and Dry creeks, near longitude 109°, and the anticline which passes through Thermopolis. There is a lower member of hard, coarse, gray to buff sandstone in massive beds and an upper member of massive shale of purplish color contain-

ing thin-beds of sandstone. In some places there is at the top a bed of gray or brown sandstone, which is 4 to 8 feet thick. In the Mud Creek region the basal sandstone is 30 feet thick, the overlying purple shales carry cherty concretions and thin layers of brown and buff sandstone, and at the top are several layers of brown sandstone. In the ridge north of Red creek, southwest of Thermopolis, the formation is about 150 feet thick and presents three bodies of sandstone separated by purplish and gray shales and thin-bedded sandstones. Along Bighorn river north of Thermopolis the basal member is 35 feet of hard, massive, light gray sandstone, conglomeratic at the bottom. Above are 20 feet of softer buff sandstone, 30 feet of purplish shale, and 6 feet of slabby dark buff sandstone which weathers brown. Southeast of Embar the formation is more than 200 feet thick and consists of two prominent sandstone members, the lower one the thicker, separated by purplish clays and shales, with thin-bedded sandstone. Southeast of Black mountain there are at the base 30 feet of hard white to gray sandstone, massive and in part cross-bedded, then 100 feet of clay, and at the top about 10 feet of hard slabby to massive sandstones which weather to a dark color. The clays between the two sandstones are of strong purple color for 30 feet or more near the top, paler below, and in the middle pale greenish gray. They contain a few layers of fine sandstone of white, buff, and greenish tints and several bands of calcareous and cherty nodules, a common feature in the Owl Creek region. On North fork of Muddy creek the basal sandstone is of very light color, and it contains in its lower portion a thick mass of white conglomerate.

Wind River-Rattlesnake mountains.—The Cloverly sandstone is much less thick in the Wind River and Rattlesnake uplifts than in the region north and east. In the ridges about Lander it is represented by buff sandstone, often cross-bedded, which is only 25 feet thick in places, but forms a characteristic hogback ridge. In Rattlesnake mountain the amount is 60 to 80 feet and the rock is a hard, massive sandstone, mostly conglomeratic, capping a hogback ridge.

Casper-Douglas-Medicine Bow region.—The Cloverly sandstone is prominent in the ridges south of Casper, especially in the two deep gorges which it causes in Platte river above and below the mouth of Poison Spider creek, the wide, high plateau of Haystack range, and the ridges near Freeland and Alcova. Much of the rock is a brown, massive, coarse conglomerate 40 to 60 feet thick. Near Freeland it is 40 feet thick (see plate 29). In Muddy Creek valley, at the east end of Casper mountain, the formation caps the usual hogback, and where vertical rises as a steep wall. The basal conglomerate is 25 feet thick, with many pebbles a half

to 1 inch in diameter, partly of jasper. This merges up into a coarse buff sandstone, followed by 60 feet of shales, mostly dark, but in part of purplish red color, and then the top sandstone. In places there are two sandstone members besides the basal one, separated by shale. The upper sandstone is thin-bedded and rusty in color. South of Douglas there are three sandstones, the basal one coarse-grained and conglomeratic as on Muddy creek. Locally the upper sandstone becomes especially prominent and is underlain by 20 feet or more of reddish clay. About Alcova the formation is about 50 feet thick and consists of dark conglomerate below and white or buff sandstone above. Near the south end of Platte canyon, 35 miles above Alcova, where the thickness is 60 feet, the basal portion is massive conglomerate containing numerous boulders up to 6 inches in diameter, including many of limestone, apparently Carboniferous. Como ridge east of Medicine Bow is capped by Cloverly sandstone, and this rock circles around the end of Freezeout uplift and the anticline north of Medicine Bow and rises in a prominent monoclinal ridge on the east side of Little Medicine valley. Here the thickness varies from 125 to 150 feet, and in the high butte on the axis of the anticline, 15 miles northeast of Medicine Bow, there are two sandstone members separated by gray and purplish shale and clay. West of Marshall, where the thickness is less, the formation appears to consist entirely of hard, gray sandstone.

Laramie basin.—In Laramie basin the Cloverly is seldom more than 200 feet thick and ordinarily the amount is considerably less. As in other regions, it consists of two sandstone members separated by buff and purplish, sandy clays. The sandstones, especially the lower ones, are usually locally conglomeratic, with pebbles of vari-colored cherts and jasper. The lower sandstone is the most prominent member topographically, often giving rise to a prominent hogback ridge. At the north end of the hogback at the east end of Centennial valley the formation consists of 10 feet of massive sandstone, 100 feet of flaggy, ferruginous sandstone and shale, and at the base 40 feet of massive, white sandstone. The latter is conglomeratic in places and lies on 30 feet of ferruginous shales which may belong either in the Cloverly or Morrison formations. Below are 300 feet of typical, bluish to purple, Morrison shales. On the south bank of Laramie river, north of Jelm mountain, the formation consists of 25 feet or more of buff, flaggy sandstone, then 60 feet of shales, greenish above, buff below, with some layers of flaggy, white sandstone, and, at the base, 23 feet of flaggy, buff sandstone. In the anticline on the south side of Hutton lake, 10 miles southwest of Laramie, a complete section of vertical beds is exposed as follows:

Section of Cloverly Formation on south Side of Hutton Lake, Wyoming

	Feet
Gray to light buff sandstone, cross-bedded below, softer above	70
Coaly shale	1½
Sandy clays, greenish buff below, black in middle, and gray near top	30
Sandy shales with two cherty layers	20
Clays, shales, and sandstones, part dark gray, part purplish	40
Sandstone, fine-grained, soft, with harder and coarser layers	40
Sandstone, light gray, massive and cross-bedded, in part conglomeratic	35
Morrison formation.	

Two miles south-southwest of Howell station, where the formation is about 50 feet thick, it consists of two massive, coarse, hard sandstone members separated by dark shale which has been prospected for coal.

East side of Laramie mountains.—On the east side of Laramie mountains the formation presents its usual tripartite character. In the small exposure north and west of Hecla the following beds appear:

Section of Cloverly Formation near Hecla, Wyoming

	Feet
Flaggy buff sandstone	10
Shale, mostly concealed	20
Buff sandstone	14
Soft, white sandstone	12
Soft, shaly sandstone	8
Conglomerate on Morrison	10
Total	74

South of North fork of Horse creek the thickness is 100 feet. Near Horse creek the sandstones are soft and are not well exposed, so that the hard, lower sandstone of the Benton is much more prominent.

Correlation.—No fossils were found in the Cloverly formation, but its relations and physical features strongly suggest that the basal sandstone is equivalent to the Lakota sandstone of the Black hills, and the overlying purple shales to the closely similar Fuson formation. Both of these are of lower Cretaceous age. The top sandstone probably represents the Dakota locally.

COLORADO FORMATION

Occurrence and general relations.—In the Colorado formation begin the thick deposits of black shale which characterize a large portion of the

FIGURE 1.—CROWHEART BUTTE, WASATCH BADLANDS ON NORTH SIDE OF WIND RIVER, NEAR MOUTH OF CROW CREEK, WYOMING

FIGURE 2.—TWO SANDSTONE MEMBERS IN UPPER PART OF COLORADO FORMATION NEAR HEAD OF MUDDY CREEK

Looking north toward Owl Creek mountains, Wyoming

CROWHEART BUTTE AND SANDSTONE MEMBERS OF COLORADO FORMATION, WYOMING

upper Cretaceous. Its thickness averages 1,200 feet. East of longitude 107° the chalky sediments of the Niobrara formation characterize its upper portion, but westward this becomes shale or shale and sandstone, not clearly separable from the Benton. Accordingly, in the map, plate 22, both formations are grouped as the "Colorado formation," while in plate 21 they are shown separate. The outcrops of the Colorado formation appear on both slopes of the Owl Creek uplift; on the east side of the Wind River uplift south from North fork of Little Wind river; on the north slope of Rattlesnake mountain; in the uplifts southwest of Casper; south of Big Muddy, Glen Rock, and Douglas; west of Ervay and on Conant creek; near Alcova; on the slopes of the uplift of Freezeout hills; on the south side of the Shirley hills; in the anticline north and east of Medicine Bow and Rock Creek; along the east side and across the south end of Laramie basin; in the Centennial syncline, near Jelm and at intervals along the east side of Laramie mountains from Chugwater creek to Crow creek. A small outlier remains on the plateau summit of the Haystack range.

Benton formation.—The Benton formation consists mainly of dark gray fissile shale, but about 200 feet below the top there is a constant horizon of moderately hard, massive to slabby, gray to buff sandstone, which usually outcrops as a distinct "hogback," as shown in plate 30. In the lower beds some sandstone and deposits of bentonite occur. The latter is a white or slightly tinted clay or hydrous silicate of alumina of peculiar porous texture. It presents some evidence of being a decomposed volcanic ash. There is also, near or below the middle of the formation, a persistent and characteristic member, the Mowry beds, which consists of from 100 to 200 feet of hard, gray shales and fine-grained, thin-bedded sandstone, which weather to a light silvery gray. They contain large numbers of impressions of fish scales. Owing to their hardness, the Mowry beds usually give rise to prominent ridges which bear scattered pine trees. Lens-shaped concretions occur in the lower and upper Benton, especially in the shale above the Mowry beds. The Greenhorn limestone, which is such a distinct horizon in the Great Plains region, is lacking, excepting along the east side of the Laramie mountains. The upper part of the Benton, however, presents all the characteristics of the Carlile formation, and the lower part is identical with the Graneros shale. This shale usually begins abruptly above the Cloverly sandstone, and there is considerable evidence of local unconformity. Locally the lower Benton beds include thin, rusty layers of irony sandstones intercalated among the shale.

Niobrara formation.—In southeastern Wyoming the Benton shale is succeeded by chalk, limy shale, and limestone, 200 feet or more thick,

characteristic of the Niobrara formation. It is conspicuous west of Laramie, on the east side of the mountains east of Laramie, about Rock River and Medicine Bow, in Little Medicine valley, about the Freezeout and Shirley hills, and on Muddy creek southeast of Casper. It also appears south and southwest of Douglas and Casper, but west of the North Platte it rapidly loses its calcareous components, and the characteristic colonies of *Ostrea congesta* cease to occur.

Wind River-Owl Creek region.—In the Wind River basin the Colorado formation varies from 750 to 1,650 feet thick, the greater amount being along the south side of the Owl Creek uplift. The stratigraphic succession is nearly uniform throughout. The lowest beds are several hundred feet of dark shale containing near the base a sandstone from 2 to 20 feet thick. Next come the Mowry beds, which average 100 feet thick and give rise to prominent round-topped ridges, which are especially conspicuous along the north side of the valley of Mud creek, in the flexures east and west of Thermopolis, and about the head of Dry creek and along the outcrops northeast and south of Lander. In places the impressions of fish scales are so abundant in the Mowry beds as to show from 5 to 10 on a surface 6 inches square. Near Fort Washakie and southwest the Mowry beds are about 500 feet above the base of the formation, but farther north there is less shale below them. Next above are several hundred feet of gray shales, the amount diminishing to the south, containing near the top one to three beds of gray to buff sandstone, usually constituting ridges, as shown in plate 30. Near Lander there are three of these beds, the top and lowest ones thin and partly shaly, the middle one hard and thick, locally attaining a thickness of 40 feet. A thin bed of coal occurs in one area which near Dallas has a local thickness of 18 inches. A fourth sandstone is included near Fort Washakie. Near the top of the formation are from 100 to 150 feet of dark shales which contain lens-shaped concretions, mostly from 2 to 3 feet in size, containing *Prionocyclus woolgari*—a form highly characteristic of the uppermost portion of the Benton (Carlile formation) in most regions. It often attains a diameter of from 14 to 20 inches. The following section, measured east of Black mountain, illustrates the stratigraphy of the formation in the western portion of the Owl Creek uplift:

Section of Colorado Formation on Red Creek, 3 Miles East of Black Mountain

	Feet
Gray, massive sandstones, mostly hard; many fossils......	15
Dark shale with sandstone beds........................	200
Light gray, sandy shale, weathering light buff.............	40
Coarse, buff sandstone..................................	10

	Feet
Dark shale	5
Dark shale, with several layers of hard, buff sandstone from 3 to 18 feet thick	200
Buff sandstone	3
Black shale	50
Light gray sandstone, massive and moderately hard	25
Brown and gray, hard, fine-grained sandstone, slabby	25
Hard, gray shales and thin-bedded, fine-grained sandstones with fish scales (Mowry beds)	250
Gray shales, containing near the middle 10 feet of hard, buff sandstone in two bodies separated by 20 feet of sandy shale	700
Sandy shale and slabby sandstone—brown, olive green, and rust color	125
Total	1,648

The 40-foot stratum of light gray, sandy shale weathers to a light buff color, somewhat suggestive of the Niobrara formation in other regions. The top sandstone and possibly part of the adjoining shales, comprising the strata down to and including the light gray sandy shale which weathers to a light buff color, may represent the Niobrara formation. The fossiliferous sandstone varies in thickness from 5 to 25 feet and is persistent along both slopes of the uplift, rising as a low but sharp ridge conspicuous in Owl Creek valley and near Dry and Muddy creeks. On the east side of the syncline east of Dry creek the beds are vertical, and this sandstone filled with fossils rises as a wall 5 to 30 feet high. S. W. Williston[17] recently examined the upper beds of the Colorado formation southeast of Lander and proposes the name "Hailey" shale for some dark blue shales, 30 to 75 feet thick, yielding saurian remains. These shales contain two thin but continuous beds, the upper one of white clay and the lower of irony shale with numerous bones and fresh-water shells. Thirty feet above the "Hailey" beds are sandstone with rare *Ostrea,* and then about 600 feet of sandstone and shale with Pierre fossils, followed by 2,000 or 3,000 feet of Pierre shale. These "Hailey" beds are believed to be Niobrara and may possibly represent the Belly River series.

North Platte basin to Rock River.—In the Rattlesnake Mountain uplift the Colorado formation presents its usual features. The Mowry beds are prominent, but only about 80 feet thick, and lie approximately 700 feet above the base of the formation. About 200 feet above the Cloverly sandstone is an 8-foot bed of gray sandstone. Toward the top of the formation is the usual bed of sandstone, 30 feet thick, and in places there

[17] Science, vol. xxii, October 20, 1905, p. 504.

are two sandstones. At the top are shales, probably representing the Niobrara. Near Clarkson the upper sandstone is conspicuous and near the mouth of Poison Spider creek there are 4 beds, the lowest 40 feet thick with ironstone concretions at its top. These sandstones give rise to prominent ridges which extend along two anticlines from North Platte river nearly to Powder river. Near Platte river, southwest of Casper, the lower shales contain a 40-foot bed of buff sandstone. The Mowry beds are 100 feet thick and overlain by 100 feet of black shale, followed by a succession of hard gray to buff sandstone and shales extending to the Niobrara limy shale, which outcrops at several localities. The lower Benton shales on Poison Spider creek, 8 miles east of Efell, contain a bed of sandstone saturated with petroleum, notably at the "oil spring." This sandstone lies about 250 feet below the base of the Mowry beds. It appears in the vicinity of Alcova, where it is about 8 feet thick, and lies midway between Mowry beds and Cloverly sandstone. The upper sandstone forms extensive ridges west of Freeland, and the chalky deposits of the Niobrara appear a short distance above. In Muddy valley, south of Big Muddy station, the Mowry beds lie on 500 feet of dark shales with thin beds of rusty sandstone. They are hard shales, 50 feet thick, which weather to light gray color and rise in low but sharp ridges bearing scattered pines. Next above are 500 feet of dark shales, capped by a very conspicuous sandstone 20 feet thick, partly massive and partly thin-bedded, which contains many upper Benton fossils. This sandstone is overlain by 200 feet of dark shales with some thin layers of sandstone and horizons of concretions; then follows Niobrara, which is about 100 feet thick and extends east to Boxelder creek. In the Medicine Bow region the upper shale of the Benton is overlain by chalky deposits of Niobrara, about 200 feet thick, which outcrop prominently in Chalk bluff east of Rock River, in banks along Little Medicine creek, in the river bank just north of Medicine Bow, and at intervals along the flanks of the Freezeout and Shirley uplifts.

Section of Benton Formation, 2 Miles Northwest of Medicine Bow, Wyoming

	Feet
Shale, gray	200
Sandstone, gray, partly slabby	40
Shale, gray	800
Shales, hard, and fine-grained slabby sandstones (Mowry beds)	75
Shales, mostly dark, weathering brownish; thin sandstones in lower part	250
Cloverly sandstone.	
Total	1,365

On the northeast slope of the Shirley uplift the upper sandstone of the Benton is 30 feet thick, and it crosses Muddy creek as a prominent ledge. It is separated from the Niobrara, as usual, by 150 to 200 feet of dark shale with concretions. Along the southern and eastern flanks of the Freezeout hills the Mowry beds lie 600 feet below the upper sandstone. In this region and again west of Difficulty there is a local bed of sandstone in the lower part of the Benton shales. North of the mouth of Medicine Bow creek the Mowry beds are about 60 feet thick and lie on 200 to 300 feet of dark shale with thin local sandstone bodies. They are overlain by 800 feet of shale, followed by the upper sandstone member and about 120 feet of dark shale with concretions, which extends to the base of the Niobrara. The upper sandstone member is prominent in the Rock Creek district, giving rise to a long sinuous ridge. Northeast of Rock River station it consists of a 4-foot ledge of massive, buff sandstone, and the overlying shale is 350 feet thick. The underlying shale contains concretions and a persistent bed of bentonite which is 4 feet thick for some distance.

Laramie basin.—The Benton shale occupies a large portion of Laramie basin and it outcrops at intervals from the foot of Jelm mountain past Laramie and Howell. It outcrops along both sides of Centennial valley and appears in small areas in the valley near Jelm and on the slopes west of Red mountain. There are extensive exposures in the vicinity of Hutton lake, southwest of Laramie; in the hills 1½ miles southwest of Howell, and in the railroad cuts a mile north of Howell. In the southern part of the basin the thickness is 700 feet, judging by a boring 10 miles southwest of Laramie, which began near the top of the formation and reached the Cloverly sandstone at a depth of 600 feet. The thickness of the steeply dipping beds in Centennial valley is between 500 and 600 feet. The rocks are mostly gray to black shales. The Mowry beds are about 200 feet above the base and consist of about 100 feet of the usual hard shales and thin-bedded, fine-grained sandstones, which weather to a light, silvery gray color and contain large numbers of fish scales. The ridges due to this member are especially conspicuous east of Jelm mountain, east and northeast of Hutton lakes, southwest of Howell, and in the anticlines near Medicine Bow, old Rock Creek station, and Freezeout hills. The sandstone member near the top of the formation is 20 to 30 feet thick and there are usually one or more thin beds of sandstone in the lower shales. Southwest of Howell station there are at the base 200 feet of dark shales, including a 5-foot bed of buff sandstone 45 feet above the top of the Cloverly sandstone. Next above are 100 feet of Mowry beds overlain by 100 feet of dark shales with dark concretions. Higher

beds are concealed. Five miles east of Jelm mountain the Mowry member is underlain by 20 feet of drab, brittle, sandy shale, 6 feet of black sandstone, 4 feet of white sandstone, and 145 feet of black shale lying on Cloverly. On Laramie river, 3 miles north-northeast of Jelm mountain, the upper Benton beds are 5 feet of black shale, 27 feet of soft, gray, heavy, flaggy sandstone, 8 feet of interbedded sandstone and shale, and 30 feet of black shale. In the syncline northeast of Red mountain, the lower 110 feet of the formation are black shales overlain by 30 feet of yellowish to gray shales, and then 10 feet of flaggy, buff sandstone containing impressions of long, narrow, willow-like leaves. On the southeast side of Hutton lake, 10 miles southwest of Laramie, the steep-dipping lower Benton beds have 100 feet of dark shale at the base, with a few thin, sandstone layers, 25 feet of gray sandstone, 30 feet of dark shale, and Mowry beds 100 feet or more thick. The lower shale also contains a bed of bentonite in this vicinity. On the east bank of Sand creek, 11 miles northeast of Red mountain, the formation contains a bed of bentonite 4 feet thick underlain by 7 inches of soft, gray sandstone.

In Laramie basin the Niobrara formation outcrops at intervals from the foot of Jelm mountain northeastward past Laramie. It also outcrops on both sides of the syncline in Centennial valley; it appears in the faulted block near Jelm, and there is another small area 3 miles west of the summit of Red mountain. For much of its course, however, it is buried beneath later deposits. The most extensive exposures are in the large hollows west of Laramie and in bluffs along Laramie river southwest of Laramie. It consists largely of impure chalk rock of light gray color which weathers bright yellow and contains large numbers of *Ostrea congesta*. The thickness is 425 feet in the sharp upturn 2 miles northwest of the Union Pacific Soda lakes, west of Laramie. The middle member is dark gray shale. The chalk rock is in beds varying from thin layers to slabs an inch or two inches in thickness, and sometimes it is sufficiently hard to give rise to buttes which are of conspicuous bright yellow color.

East side of Laramie mountains.—On the east side of Laramie mountains the Benton consists mainly of shale, but several members are recognizable. The Greenhorn limestone of other regions is represented by a thin layer of impure slabby limestone containing the characteristic *Inoceramus labiatus*. The Mowry member is distinct, and near the base of the Benton there are 15 to 20 feet of hard sandstone, in most places rising in a small, sharp ridge often more conspicuous than the Cloverly sandstone. A representative section in vertical beds near Horse creek is as follows:

Section of Benton Formation West of Horse Creek Station, Wyoming

		Feet
Carlile	Black shale (overlain by Niobrara limestone)	10
	Sandstone and sandy shale	20
	Gray shale, with concretions containing *Prionotropis* near top	200
Greenhorn	Sandy limestone with *Inoceramus labiatus*	¼
Graneros	Shale, dark and fissile below	350
	Hard shale and thin-bedded, fine-grained, hard sandstone, weathering light gray; many fish scales (Mowry beds)	80
	Dark shale	30
	Hard, coarse sandstone, massive	25
	Dark shales, fissile to soft, on Cloverly sandstone	150
	Total	865¼

Some of these measurements are uncertain, owing to talus or crushing. Near North fork of Horse creek the top member is 15 feet of slabby gray sandstone with some shale, lying on 20 feet of shale with oval concretions. The Greenhorn limestone layer is about 1 foot thick, but yielded no fossils. In this vicinity the Mowry beds lie 500 feet below the Niobrara and grade down into 30 feet of black shale. The latter is underlain by 25 feet of fine-grained, hard, white sandstone separated from the Cloverly by 200 feet of black fissile shale. This lower sandstone is conspicuous in ridges south, east, and north of Iron Mountain station, where it is 25 feet thick and lies on 125 feet of dark shale. Above it are 50 feet of dark shale, grading into Mowry beds. The Niobrara formation appears extensively at intervals from Lodgepole creek to Chugwater creek, east of Laramie mountains. A small outcrop occurs on Crow creek. West of Horse Creek station it is 375 feet thick and consists of limestone and limy shales, with a massive bed of limestone at the base containing *Inoceramus deformis.* Another bed of limestone occurs near the middle, while at the top are impure shaly limestones which weather to a bright yellow color. Slabby aggregates of *Ostrea congesta* occur in many of the beds, and this fossil also occurs disseminated in some of the layers. Near North fork of Horse creek the formation is 400 feet thick.

Fossils.—The principal fossils of the Benton formation are the very numerous fish scales in the Mowry beds and molluscan remains and saurian and fish bones and teeth, which occur at various horizons. In the upper sandstone, near the foot of Jelm mountain, were found *Inoceramus fragilis,* together with fish teeth apparently of *Ptychodus* and *Lamna.* The upper sandstone also contains *Prionocyclus,* a fossil which is charac-

teristic of the upper portion of the Benton in a wide area of the Rocky Mountain and Great Plains provinces.

The Niobrara chalky beds contain large numbers of *Ostrea congesta.* In sandstone high in the Benton, on Muddy creek south of Big Muddy, *Inoceramus fragilis* and *Cardium paupereulina* occur in abundance. In Wind River basin, in the vicinity of Dry creek and farther west toward the base of Black mountain, the top sandstone of the Colorado formation is highly fossiliferous, containing the following species, which have been identified by Mr T. W. Stanton: *Ostrea coalvillensis* Meek, *Ostrea sannionis* White, *Anomia* sp., *Pecten* sp., *Inoceramus erectus* Meek, *Gervillia* sp. cf.,*G. propleura* Meek, *Cardium curtum* M. and H., *Cardium* sp., *Anatina* ? sp., *Turritella spironema* Meek ?, and *Baculites compressus* Say. Mr Stanton states that they belong to a faunule that occurs in the upper part of the section at Coalville, Utah, and is also found in western Wyoming occupying the stratigraphic position of the Niobrara or not far above it. At no great distance above the sandstone occur distinctive Pierre fossils.

MONTANA FORMATION

Occurrence and general relations.—The Montana formation underlies large areas in Wyoming, mainly in the many wide synclines between the larger uplifts. It is extensively overlain by formations which have been termed Laramie and Fort Union and widely overlapped by various Tertiary deposits. In central Wyoming it outcrops along the east slope of Wind River uplift east of longitude 109°, along the south side of Owl Creek uplift between Muddy and Dry creeks, across the south side of Bighorn basin, along the north side of the Rattlesnake Mountain uplift, in a broad belt extending through Casper to and down the South Powder valley, in the basins between Casper and Alcova, along the south side of Shirley hills, along the Muddy Creek-Medicine Bow basin, in a large portion of Laramie basin, and at intervals along the east side of Laramie mountains from Chugwater creek to Crow creek. The lower rocks for 2,500 feet or more present all the characters of Pierre shale. They are overlain by sandstones, shales, and local coal measures representing the Mesa Verde, Lewis, and Fox Hills formations. The upper division occurs in the Wind River and Laramie basins, in a small area north of Freezeout hills, and in the broad basin which extends far to the east and northeast from Casper and Douglas. Both divisions appear also on Horse, Lodgepole, and Crow creeks east of Laramie mountains, which indicates that they underlie the Tertiary deposits for some distance under the Great Plains.

Wind River basin.—The broad syncline between the uplifts of Wind River and Owl Creek mountains holds a great thickness of Montana formation, but it is mostly covered by Tertiary deposits. Outcrops appear in the valleys of Muddy and Dry creeks, in the broad belt extending through Fort Washakie and Lander, and on the uplifts on Conant and Muskrat creeks. The lower division, or Pierre shale, consists of a monotonous succession of soft, dark gray shales with intercalated thin beds of sandstone in their upper part. Their thickness is 2,600 feet on Dry creek, 2,250 feet on Muddy creek, where the beds are nearly vertical, and over 3,000 feet east of Lander. The upper division consists of sandstones with intercalated gray shales and sandy shales and local coal beds. The first bed of sandstone, from 200 to 250 feet thick, is usually succeeded by sandy, carbonaceous shale which develops locally into coal. This coal is 8 feet thick for a short distance in the coal field 10 miles east of Lander and about 3 feet thick on Muddy creek. The upper division attains a thickness of 550 feet before it disappears under the Tertiary east of Lander, and about the same amount appears in the ridges on Muddy creek. In the uplifts on Conant and Muskrat creeks and on the north side of Rattlesnake mountains the Montana formation presents features similar to those described above.

Laramie basin.—In the deep syncline west and northwest of Laramie the lower division of the formation consists of 2,500 to 4,000 feet of dark shales, with occasional thin beds of sandstone and numerous nodular concretions. The sandstones are seldom over 5 feet thick and are separated by from 100 to 300 feet or more of dark shales. Toward the top the sandstones rapidly increase in number and frequency, and in places they constitute a passage series into the upper division. The latter usually begins with a prominent bed of hard, gray sandstone 60 to 80 feet thick. This sandstone outcrops most conspicuously in "Pine ridge," which extends along the Union Pacific railroad 2 to 3 miles southeast of Rock Creek station; on the bank of Little Laramie river 17 miles northwest of Laramie; in a high knob 4 miles northeast of Sheep mountain; in a ridge extending southward from Rock Creek station, and in the syncline along the foot of Medicine Bow mountains 10 miles northeast of Centennial. It crosses Laramie river at Dun's ranch, 13 miles southeast of Rock Creek station. Generally this sandstone contains concretions of harder rock and some darker gray layers. It is overlain by a variable thickness of softer sandstone of various kinds, followed by a succession of shales and sandstones. The amount of sandstone in this member increases to the southward. Some of the rocks are carbonaceous and locally develop into coal from a few inches to 4 feet or more thick. The most persistent coal

bed lies next above the heavy sandstone members in the Rock Creek region, but there are also higher beds farther south. These coal deposits have recently been described by Mr Siebenthal.[18]

A typical section of the Montana formation was measured by Mr Siebenthal, as follows:

Section of Montana Formation Southeast of Rock Creek Station, Wyoming

		Feet
Upper division	Shale	140
	Brown sandstone, partly concretionary (*Inoceramus*, etcetera, Upper fossil horizon)	5
	Soft, gray sandstone with hard concretions	10
	Buff shale	200
	Concretionary sandstone (gasteropods, baculites, etcetera)	5
	Gray sandstone	12
	Buff shale	150
	Massive, disintegrated, gray sandstone; no fossils.	20
	Shale	125
	Massive, buff and brown, concretionary sandstone (baculites)	15
	Black shale with beds of coal	560
	Shaly sandstone and shale ("Pine ridge" coal)	30
	Massive white to gray sandstone; some shale in lenses (sandstone of "Pine ridge")	60
		1,332
Lower division	Shale	300
	Brown sandstone, round concretions (very few fossils)	5
	Shale	225
	Sandstone nodules (probably contain fossils)	2
	Shale	240
	Concretionary sandstone (main collection of fossils)	15
	Shale	300
	Brown sandstone, with oval concretions (few fossils)	3
	Shale	115
	Gray sandstone (plants, baculites ?)	5
	Shale	425
	Shale and claystone lenses (baculites)	10
	Shale	150
	Sandstone, with round concretions	5
	Black shale, with thin beds of nodular sandstone	2,350
	Niobrara.	
		4,150

[18] U. S. Geological Survey, Bulletin no. 316, pp. 261-263.

For many miles along the foot of Medicine Bow and Sheep mountains the Montana formation is faulted against the pre-Cambrian granites and schists. Farther north, in Carbon county, it is overlapped by sandstones which Mr Veatch regards as a higher, or true Laramie, formation. In this region Mr Veatch divides the Montana into Pierre shale and Mesa Verde sandstone, while the upper shale is regarded as equivalent to the Lewis shale of Colorado.

East of Laramie mountains.—At the foot of the mountains the Tertiary is cut through by Crow, Lodgepole, and Horse creeks, and the Montana and underlying strata are revealed. The outcrop of nearly vertical Pierre shale is over a mile wide on Horse creek. It gives place above to gray sandstone in which the dip rapidly diminishes, so that only a few hundred feet appear. This sandstone with low dips occupies a wide outcrop zone west of the railroad, on the Middle and North forks of Crow creek.

Fossils.—Molluscan fossils occur in large numbers in the Pierre shale, or lower division of the Montana formation, throughout central Wyoming, but very few were collected outside of Laramie basin. Fossil leaves occur in the coal-bearing members, and, as shown by the geologists of the Fortieth Parallel Survey, and again, ten years ago, by Stanton and Knowlton, the marine Montana fauna, Pierre-Foxhills, recurs above the plant-bearing beds.[19] These latter observers examined the region lying between Coopers creek and Rock river. A few miles southeast of Rock River station, where the sandstone associated with the lower coal bed is 40 feet thick, plants were obtained, while in shales 100 feet or more above were found *Baculites ovatus, Chlamys nebrascensis,* and *Inoceramus cripsii* var. *barabini.* Near the railroad cut along the foot of "Pine ridge," 2 miles southeast of Rock Creek station, where the same sandstone is 60 feet thick, additional plants were found, while in shale 500 to 600 feet higher occur *Baculites compressus, B. ovatus, Avicula nebrascana,* and some other forms. The shales below the prominent sandstone contain many fossils, mainly in the thin beds of hard sandstone which are included. Stanton and Knowlton gave a long list of typical Pierre fossils from one bed 400 to 500 feet below the coal and from another horizon 300 to 400 feet lower. They also reported fossil plants from the lower sandstone of the upper division of the Montana where it crosses Laramie river at Dun's ranch, northwest of Howell, but the plants were not all the same as in the region nearer Rock Creek station. Additional plants were obtained at the small coal mine on the North fork of Dutton creek, near the old stage road, where two of the species are the same as found

[19] Bulletin of the Geological Society of America, vol. 8, 1897, pp. 127-158.

near Rock River station. Three miles southwest, near the old stage road crossing of Cooper creek, they found in higher beds 25 species of a characteristic Fox Hills fauna. Plants were collected also at the "Dutton Creek" coal mine, 6 or 7 miles northwest of the coal mine above referred to. Owing to the limited exposures, the stratigraphic relation of the beds was not clear, but they appeared to be at a higher horizon than the older localities. Stanton and Knowlton concluded as follows:

> It is evident from the preceding that the coal-bearing series of the Laramie plains is in large part, if not wholly, older than the true Laramie, as that formation is usually defined, although it yields what has been supposed to be a Laramie flora; that is, instead of conformably overlying the Fox Hills beds, it is overlain by them or included within them."

Marine fossils were collected from the Montana beds at two localities by Mr Siebenthal and determined by Mr Stanton. The species from Bengaugh's ranch, on Cooper creek near the Albany-Carbon county line, are: *Inoceramus cripsi* var. *barabini* Morton, *I. sagensis* Owen, *Ostrea pellucida* M. & H., *Avicula linguiformis* E. & S., *A. nebrascana* E. & S., *Pectunculus wyomingensis* (Meek), *Modiola galpiniana* (E. & S.), *Tancredia americana* M. & H., *Callista* (*Dosiniopsis*) *nebrascensis* M. & H., *Baculites ovatus* Say, *Helicoceras mortoni* var. *tenuicostatum* M. & H., *Placenticeras intercalara* M. & H., and *Leptosolen volutomorpha*, (?) *Actæon*, and *Heteroceras*. From beds slightly higher were obtained *Inoceramus cripsi* var. *barabini* and *I. vanuxemi*. From beds above the sandstone in "Pine Ridge," 2 miles south of Rock River station, Wyoming, were obtained *Avicula linguiformis* E. & S., *Inoceramus cripsi* var. *barabini* Morton, *Protocardia subquadrata* E. & S., *Baculites ovatus* Say, *B. compressus* Say, *Micrabacia americana* M. & H., *Ostrea*, *Lucina*, *Capulus*, *Anomia*, *Pentacrinus*, and *Serpula*. Fossils collected by me at various localities west of Laramie were determined by Mr Stanton. The upper beds of the lower division yielded *Inoceramus barabini*, *Mactra gracilis*, *Cardium speciosum*, and the latter also occurs abundantly in higher beds near Sheep mountain. The massive sandstone at the base of the upper division is highly fossiliferous on the bank of the Little Laramie river at J. Ernest's ranch, 17 miles west of Laramie. It yielded *Inoceramus barabini*, *I. sagensis*, *Avicula linguiformis*, *A. nebrascana*, and *Baculites compressus*. In a slightly higher sandstone east of Sheep mountain I found a cast of an egg case of a fish classed by Dr Gill in the *Harriotta*.[20]

In the upper beds of the lower division (Pierre), 14 miles northwest of Howell, I discovered a skeleton of a saurian which Mr W. H. Reed, of Laramie, has identified as Cleosaurus. A collection of fossils

[20] Science, vol. 22, 1905, pp. 601-602.

from the lower sandstone of the upper division, 2 miles south of Glen Rock, comprised the following species identified by Mr Stanton: *Anomia* sp. *Avicula linguiformis, A. nebrascana, Modiola meeki, Lunatia occidentalis, Haminea occidentalis, Callista deweyi,* and *Scaphites modosus,* all upper Montana forms.

Tertiary System

No detailed examination was made of the Tertiary deposits, but the limits of the larger areas were determined, as shown on the maps. The Wind River basin and broad divide north of Rattlesnake mountains contains a very broad belt of sands, sandstones, and clays, belonging mainly to the Wasatch formation (see plate 30). It extends eastward across the Powder River-North Platte divide, and thence southeastward in the high plateau which ends a short distance west of Alcova. To the south, in the Sweetwater plateau, it is overlain by the Sweetwater formation of the Hayden Survey. The latter formation strongly suggests the White River, into which it appears to merge in the high plateau west of Alcova. In the upper part of Wind River valley the Wasatch is overlapped by a thick series of later Tertiary volcanic rocks with intercalated shales and sandstones, which are part of the great area extending through Yellowstone park. The wide area of Tertiary constituting the high plateau extending south from Bates creek and into the valley of Little Medicine creek is mainly White River. It consists of light colored sandy clays, of which the basal member is the Chadron formation, or Titanotherium beds. The latter and the overlying Brule clay also occupy areas west, south, and southeast of Douglas and extend far up some of the mountain valleys south. They are revealed again in the valleys of Crow, Lodgepole, and Horse creek nearly to longitude 105° and down Chugwater creek to a point 8 miles south of Wheatland. They pass beneath the Arikaree formation, which consists mostly of sands and soft sandstones with basal conglomerate. This formation thickens rapidly to the east and north and extends far up the Laramie Mountain slopes on the divides and into some of the higher valleys. It is on this formation that the Union Pacific railroad grade rises nearly to the eastern crest of the Laramie mountains. An area of sandy clay resembling Wasatch in appearance occupies a basin on Dutton-Cooper creeks. Small outlying areas of unknown age lie on the mountain slopes south of Centennial and west of Red mountain.

Geologic History

In General

The rocks of central Wyoming are the products of Middle Cambrian to Recent time, but several important periods are not represented and parts of the geologic history are very obscure.

To the southeast, where the pre-Cambrian rocks are directly overlain by later Carboniferous deposits, the history of the long Cambrian, Ordovician, Silurian, and early Carboniferous periods is not apparent.

Early Paleozoic Conditions

Judging by absence of deposits and by overlap relations, a large portion of the Rocky Mountain province was a land surface in earlier Paleozoic times. The lands were probably large islands, which were to some degree coextensive with the present mountain province, but the peripheral shores are not even approximately determined for any one epoch and the relations of land and sea varied greatly from time to time. Doubtless there were intervals of partial submergence with deposition of materials which have been more or less completely removed in succeeding uplifts.

Cambrian Sea

The great interior seas of Cambrian time apparently did not cover all of the Rocky Mountain province, and even in the deepest submergence in the Middle Cambrian the present Laramie range and some adjoining regions were islands probably in an extensive archipelago. In central Wyoming, however, there were marine conditions for a while, as shown by several hundred feet of Middle Cambrian sediments. Much local material was deposited in this epoch, especially in the earlier stages, but finer grained muds were also laid down. The limestone conglomerates at the top of the Deadwood formation indicate recurrence of shallow water conditions, probably the beginning of emergence which lasted through the latter part of Cambrian and the earliest part of Ordovician time. During this epoch the land area extended widely over the northern Rocky Mountain province. How much of the Cambrian was eroded is not known, and therefore it is not feasible even to suggest the location of the shorelines of Middle Cambrian deposition.

Ordovician Submergence

During the Trenton epoch much of Wyoming was submerged and a thick body of limestone laid down. The southern limit of deposition

apparently passed east and west across central Wyoming from the southern part of the Bighorn uplift to the south end of the Wind River range.

SILURIAN-DEVONIAN HIATUS

From the close of the Trenton to early in Carboniferous time central Wyoming presents no record, the later Ordovician, Silurian, and Devonian being absent. Whether the region was land or sea, or alternated from one to the other condition, is not known, but there is no evidence of extensive uplift or deposition. Any deposits laid down are gone now in the wide area in which the Carboniferous lies on Middle Cambrian or older rocks.

CARBONIFEROUS SEA

Early in the Carboniferous period there was deep marine submergence in a large part of the northern Rocky Mountain province, and a thick deposit of limestone resulted. It covered Ordovician sediments in northern and north central Wyoming, but overlapped onto Middle Cambrian and pre-Cambrian rocks to the south. The submergence did not reach the area now marked by the Laramie range until late in Mississippian time, and then only covered its northern end. The sediments were mostly carbonate of lime. In later Carboniferous (Pennsylvanian) time, however, the waters covered most, if not all, of the province, and many of the sediments were the coarse materials of an advancing shoreline. In these times the old crystalline rocks of the lands, having been deeply eroded, decomposed, and completely oxidized, furnished a large amount of coarse material and much red clay. When the waters had deepened somewhat limestones were deposited, but there were intervals in which sands and red muds were the principal deposits, especially far to the south and southwest, where these materials predominated because of shallower water and stronger currents in that direction.

RED GYPSIFEROUS SEDIMENTS

In the later part of Carboniferous time, and probably during the Permian also, there was widespread emergence, resulting in shallow basins with very wide mud-flats which occupied a large portion of the Rocky Mountain province. In these regions were laid down the last deposits of the Pennsylvanian division and the great mass of red clay and sands constituting the Chugwater formation. These beds probably were largely deposited by saline water under arid climatic conditions and accumulated in a thickness of 1,000 feet or more. The waters were shallow much of

the time, and there were wide, bare wash-slopes and mud-flats, as is indicated by the frequent mud-cracks, ripple-marks, and impressions of various kinds on many of the layers throughout the formation. The nearly general red tint of the deposits doubtless was the original color, for it is present not only throughout the extent of the formation, but also in most beds through its entire thickness, as is shown by deep borings. At various times accumulation of sand and clay was interrupted by chemical precipitation of comparatively pure gypsum in beds ranging in thickness from a few inches to more than 67 feet and usually free from mechanical sediment. It is apparent that this gypsum is the product of evaporation while mechanical sedimentation was temporarily suspended—a condition indicative of greatly diminished rainfall; otherwise it is difficult to understand its nearly general purity. The Chugwater red beds have been supposed to represent the Triassic, but in part at least they are probably Permian. Their deposition appears to have been followed by extensive uplift without local structural deformation, but with general planation and occasional channeling which represents a portion of Triassic time of unknown duration. It was succeeded by the deposition of later Jurassic sediments.

JURASSIC TO CRETACEOUS SEAS

The absence of Jurassic sediments in the central and southern portions of the Rocky Mountain province indicates that this region either was a land area throughout Jurassic time or that any Jurassic deposits laid down were removed by late Jurassic or early Cretaceous uplift and erosion. The southern margin of the area of known Jurassic deposition passed across the middle portion of the Laramie basin, but it extended farther south along the front range of the Rocky mountains to a point in Colorado a few miles south of the Wyoming boundary. That this submergence was marine is indicated by the fossils.

The area of Jurassic deposition extended far to the north through Wyoming and Montana, to the northeast beyond the Black hills, and probably a hundred miles or more east of the Laramie mountains. The materials are fine-grained, especially in the upper beds, which are mostly shales, and therefore indicate the absence of strong currents.

During the long portion of Mesozoic time which followed the marine Jurassic there were deposits of various kinds, but generally uniform over wide areas, gathered in a great series, beginning with such as are characteristic of shallow waters along a coastal plain, passing into sediments from deep marine waters, and changing toward the end to fresh-water

sands and clays with marsh vegetation. The first deposits now constitute the Morrison formation—a widespread mantle of massive sandy shales which extends through the Rocky Mountain province from Montana to New Mexico. The materials were laid down in a shallow body of fresh water with wide mud-flats, and the deposits were mixtures of clay and fine sand with thin, irregular bodies of coarser sand deposited by streams or currents. Occasional thin beds of impure carbonate of lime were also formed. Huge dinosaurs were numerous, for their remains are now found in abundance in the formation.

Morrison time was succeeded in the early Cretaceous by a rapid change to widespread coastal plain conditions, under which the coarse-grained, massively bedded conglomerates and sandstones of the Cloverly (Lakota) were deposited. Although the deposits change abruptly and there is occasional local channeling of the surface of the soft Morrison shale, there appears to have been only the small amount of erosion that would be expected from the strong currents which carried the coarse Cloverly deposits. If there had been any great interval of uplift and erosion following Morrison deposition, the soft clay would have been widely removed. The coarse deposits of the Cloverly sandstone were derived from sources not clearly located and spread by currents over a wide area. The coarse-grained lower member, usually about 50 to 60 feet thick, gives place to a medial member of clay mostly of purplish color, not unlike the Morrison beds, which is believed to represent the Fuson formation of the Black hills. It appears to extend southward into a member of the Comanche group. The top sandstone, resembling the Dakota sandstone of other regions, indicates a resumption of the strong currents which deposited the sands of the basal member of the formation.

Following the deposition of the great sheet of sandy sediments of Cloverly-Dakota time, there was a rapid change to clay deposition, of which the first representative is the widespread Benton shale. This inaugurated the vast Later Cretaceous submergence in which marine conditions prevailed, and it continued until several thousand feet of clay were deposited during the Benton, Niobrara, and Pierre epochs. In Benton time there were occasional deposits of sand, and one of them, in the latter part of the epoch, was general over the greater part of the northern Rocky Mountain region. Another marked episode was that which resulted in the deposition of the thin Greenhorn limestone in the middle of the Benton sediments along the east front of the Rocky mountains from the Black hills to New Mexico and far eastward into Iowa. The great extent of this highly characteristic limestone is an impressive feature, for it indi-

cates a uniform condition of sedimentation over an area of many thousands of square miles. The shale of the Benton was followed by several hundred feet of sediments, now constituting the Niobrara formation. The material was mostly impure chalk in the central portion of the province, but this gave place to shale and sandstone farther northwest. This epoch was succeeded by the Pierre, in which a thick mass of shale was deposited under very uniform conditions. The retreat of the late Cretaceous sea began in the later Montana or Fox Hills epoch, when a widespread mantle of sands was laid on the great series of clays. With farther retreat of the sea extensive land surfaces were exposed, diversified by large bodies of brackish or fresh water, which received the sands, clays, and marsh deposits of the end of the Cretaceous period. Marine conditions recurred locally in later Montana time, as shown by recurrence of the characteristic fauna in shales overlying the earlier coal measures. Whether or not the late Cretaceous sediments were deposited over the area now occupied by the Laramie mountains and the similar uplifts is not definitely known, but it is possible that they were, as they are upturned along the sides of the various uplifts. The conditions in central Wyoming during Fort Union, Denver, and Arapahoe times are not known.

EARLY TERTIARY MOUNTAIN GROWTH

There was extensive uplift in the Rocky Mountain province in early Tertiary time. This fact is clearly indicated in most of the mountain regions by the occurrence of Eocene and Oligocene deposits lying on eroded surfaces having the general outlines of the present configuration. A very great amount of material was eroded from the higher parts of the uplifts, and while a portion of it is represented by various formations, much has disappeared. Broad areas were baseleveled at this time, and it is believed that the old plain on top of Laramie mountains is of early Tertiary age, and has since been considerably uplifted. There are no traces of the Wasatch and Bridger formations east of the Laramie mountains, and they have not been identified with certainty in the Laramie basin. It is probable that there was some deposition in southeastern Wyoming in that portion of early Eocene time, but if so the deposits were removed there prior to the Oligocene time; so that the local conditions are not known.

OLIGOCENE TO PLIOCENE DEPOSITION

In later Tertiary times, after the outlines of the great mountain ranges had been developed, there was a long period in which streams of moderate

declivity flowed across the Great Plains region and through many of the wider valleys between the mountains. These, with frequently varying channels and extensive local lakes, due to damming and the sluggish flow of the water, laid down the widespread mantle of the White River deposits of Oligocene age. The first of these were the sands of the Chadron formation, which occur partly as channels filled with coarse sandstone and show clearly the course of old currents. Later, in slack water and areas of overflow, fine sands, clays, and fullers' earth were laid down to a thickness of a hundred feet or more. Some thin but very widespread sheets of limestone at or near the top of this formation indicate the presence of extensive fresh-water ponds.

The Brule clays, which follow the Chadron beds, indicate a continuation of stream deposition, but with currents less strong and with more extensive local lakes and slack-water overflows. The almost general fine-grained character and regular bedding of the Brule sediments indicate that stream declivities either were low or rapidly became so. The original extent of the White River deposition is not known because so much of the formation has been removed by erosion.

At the beginning of Miocene time the general conditions had not changed materially, but the great silt-depositing streams were given increased declivity doubtless by general uplift. They first eroded the surface of the Brule clay and other earlier formations, and then deposited upon them a sheet of sands at first with many local deposits of coarse gravel and boulders. This was the Arikaree formation. It was spread widely over the central plains region, and in some areas attained a thickness of nearly 1,000 feet—a flat alluvial fan of wonderful extent. It was deposited far up the east slopes of the Laramie mountains and buried some of the lower ridges. This time was followed by a long epoch of general uplift and gradual erosion, which in the central Wyoming region continued through the remainder of Tertiary time, and some of the erosion products were carried away by streams and spread over portions of the country east and south.

QUATERNARY CONDITIONS

At the beginning of the Quaternary time all the broader topographic features of today were outlined and largely developed. The streams had not cut their valleys so deep and the wide plains of Tertiary deposits were more extensive. During the Glacial epoch there were numerous glaciers of moderate size on parts of Wind River and Bighorn mountains

and Medicine Bow range, but no trace of their presence has been found on the Laramie mountains or Black hills. As Quaternary time progressed, the streams spread wide bodies of alluvial deposits along the wider valleys, and in later times, as the streams cut to lower levels, these deposits remain on higher terraces.

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SHORELINE STUDIES ON LAKES ONTARIO AND ERIE[1]

BY ALFRED W. G. WILSON

(Read before the Society December 31, 1907)

CONTENTS

[1] Manuscript received by the Secretary of the Society April 8, 1908.

General Character of the Basins of both Lakes

TOPOGRAPHY OF THE BASINS—COMPLEX

The general character of the topography of the basins of the different lakes can be most readily understood from the standpoint of a physiographer by describing the region as an ancient belted coastal plain subsequently modified by glacial ice. The inner lowland, that bounded on the south and southwest by the Niagara cuesta, is occupied in part by the Georgian bay and in part by the bed of lake Ontario, there being also in Ontario an unsubmerged portion of this lowland lying between the two bodies of water just mentioned. The outer lowland, bounded by the margin of the Cumberland plateau, is in its lowest parts occupied (in part) by the beds of lakes Erie, Huron, and Michigan. The waters of Georgian bay, which is confluent with lake Huron, cover parts of the inner and innermost lowlands, and in this area the escarpments separating the three lowlands are partly submerged at the present time.

There seems to be little doubt but that immediately prior to the advent of the Glacial period the topographic features of the rock-basins of the Great Lakes region were developed in all their essential features at least as much as we find them today. During the Glacial interval the topography already developed was modified both by degradation and aggradation within the basins, so that at the time of withdrawal of the last ice-sheet the relatively simple topography of the rock-basins had become more complicated by the superposition in many parts of the basins of till and other glacial materials. During the interglacial intervals the glacial debris of the earlier periods was variously shifted by aggrading and degrading agencies. During the Great Lakes period immediately following the last Glacial epoch, while the bedrock topography was little modified, we find that in places the glacial materials were partially eroded, and that the eroded material was deposited elsewhere. Although the total amount of material thus shifted was large, relatively it was too small to have any great effect in modifying preexisting topography in the basins now occupied by the waters of the Great lakes.

INITIAL CHARACTER OF THE SHORELINES

We find that the initial topography of the basins was somewhat complex. In small part the lakes were bordered by portions of bedrock topog-

raphy of the pre-Glacial cycle, modified it is true by glacial scouring. In larger part they were bordered by morainic materials of different types and by lacustrine deposits.

The initial shorelines would be uneven and irregular, and the materials bordering these shores would be of very diverse character—hard rock, almost equally hard clay, soft shales, and softer sands and gravels. Prominent headlands would be formed by some drumlins and moraines, while elsewhere low sand flats would be formed by some glacial sand plain, or long narrow points by the partial submergence of cuesta ridges.

Features of the present Shores

LAKE ONTARIO

Shore-cliffs.—At the present time there are many places where the lake shore is bordered by a sea-cliff cut in glacial debris or in bedrock. In the great majority of cases there is a beach of shingle and sand between the base of the cliff and the water; still there are some localities where the water reaches to the foot of the cliff. As the shores are visited from year to year, the conditions have been found to vary. The periodical fluctuations in the water level, apparently due to variations in the annual rainfall over the whole basin of the Great lakes, may in part be responsible for some of these changes. In some years there are quite extensive stretches on the north shore of lake Ontario, where the waves attack the very foot of the sea-cliffs. At the present time (1908) the only localities where the water when quiet reaches to the base of the cliffs occur along the shore at several places west of Lorne Park, where the sea-cliffs are cut in Medina shales.

The beaches around the shores of lake Erie are characteristically wider and of gentler slope than those on lake Ontario; probably this is because lake Erie beaches are more frequently sand beaches, while on Ontario gravels predominate. Erie is also a much shallower lake and of greater area than Ontario, and its waves would be modified and more easily influenced by bottom conditions.

While in its initial stages the shoreline of lake Ontario was very uneven, the subsequent operation of shore processes has tended to reduce the smaller irregularities and to straighten all shorelines. We accordingly find that headlands have been reduced, spits and bars have been built across the intervening bays, more or less completely closing them, and a nearly continuous beach of loose waste has been formed.

Bay-bars and spits at the east end of the lake.—South of the mouth of Stony creek, at the east end of lake Ontario, for about 21 miles there

is a nearly continuous strip of wide beach, the greater part of which consists of sand with some gravel. There is reason to believe that the initial topography of the district was that of a series of confluent river valleys divergent toward the northeast. The glacial modifications were very slight, and consisted largely in the addition of a surface blanket of loose waste. In the early history of the present lake partial submergence of these valleys produced a number of deep bays with rocky points between. At the present time all of these bays are cut off from the main lake by the series of bay-bars under discussion.

From its position with reference to the open lake, the coast is exposed to the direct action of winds and waves, which have the full sweep of the lake. Master storms would advance on the beach front almost normal to its face. The character of the material of which the bars are built shows that it did not come from the north. Material brought by shore transportation from the west would nearly all tend to be deposited in the southeast corner of the lake, southwest of Port Ontario, by reason of the form of the shore at this locality. Very little, if any, of it would move northward along the beach. An investigation of the beaches themselves shows numerous minor irregularities, with no systematic development of offsets or overlaps, conspicuous features of several barrier beaches elsewhere on the lakeshore where longshore transportation is undoubtedly the dominant factor in their construction.

In the initial stages the interbay headlands undoubtedly supplied a small amount of material to construct wing-bars on each side of each headland. The present bars, however, contain an enormous amount of material, far more than could have been supplied by the preexisting headlands, assuming topographic forms and conditions to have been even moderately uniform and similar to that over the area adjacent to the shoreline. Hence not only directly, but indirectly, are we led to the conclusion that these bars have been built up by material thrown up from the bottom of the lake by waves.

The barrier bars at Wellers bay, Big Sandy bay (West lake), and Little Sandy bay (East lake), in Prince Edward county, are also barriers of this class. There is reason to believe that the amount of material that could possibly have been supplied by the adjacent headlands would have been too small to construct them. They also have probably been built from waste cut by the waves from the bottom above wave base.

The form of the shoreline here produced is an excellent example of the tendency of shore processes to reduce a complex shoreline to as relatively a simple form as possible during the initial stages of its history.

Barrier beaches.—Small barrier beaches inclosing lagoons are found at several localities along the north and south shores of the lake. In practically every instance they are to be attributed to the action of longshore transportation, which has built them from materials derived from the adjacent sea-cliffs. The more important of the bays or harbors inclosed by these barriers are Burlington bay, Frenchman bay, Whitby harbor, and Port Darlington harbor on the north shore; Little Sodus bay, Big Sodus bay, and Irondequoit bay on the south shore.

The largest and most important of these barrier beaches is that at the west end of the lake, known as Burlington beach. This consists of a low beach ridge, built of sand and gravel, stretching across the west end of the lake in such a way that it forms the third side of a triangular bay, nearly equilateral in outline, at the west end of the lake. The bar has a surface width of about 500 yards and a length of nearly 7 miles from shore to shore. The greater portion of the material in the beach came from the east along the south shore. At the north end, however, much of the waste evidently came from the north shore of the lake.

Special features: Presque Isle tombolo.—Lying about 2 miles off the north shore of lake Ontario a few miles east of Lakeport is a low cuesta of Trenton limestone, the crest of which lies nearly parallel to the mainland. This rocky ridge, once probably an island, is now tied to the mainland by a long sand bar. At present the tie bar is about three-quarters of a mile in width at its narrowest point. The bar is concave westward and its outer end is attached to the west end of the rock cuesta. The beach is built of sand and gravel and presents a broad, slightly terraced slope to the west. The sands and gravels of which it is built have been transported from the west along the shore. They were derived from a series of low sea-cliffs cut chiefly in interglacial sands and gravels.

Back of the beach is a series of sand dunes rising about 50 feet above lake level. The dune belt is about a quarter of a mile in width. The greater portion of it is stationary, but in a few places the sand is slowly overwhelming the marshes and woodlands which lie east of it, on the earlier built portions of the bar. The east side of the bar is overgrown with marsh grasses and slopes gently down below the level of the water of Presque Isle bay.

Toronto island.—The harbor of Toronto is formed by a flying spit, composed of gravel and sand, which lies about 2 miles offshore (at the west end). The eastern end of the spit is connected with the mainland near the eastern city limits by a long, low, narrow bar. The length of the bar and spit together is about 4½ miles. At the western or free end the gravels have been looped northward.

A study of old maps of Toronto harbor shows that there has been a progressive growth westward since the first map was prepared, in 1793. The record of successive recurvements at the western end of the island is still preserved in the numerous lagoons found on the island at this end. Sir Sanford Fleming,[2] in an able article read before the Canadian Institute in 1850, attributes the groundwork of the peninsula to the Don river. The peninsula proper he attributes solely to the mechanical action of the waves. The sand and gravel of which it is composed he considered to have been transported from the eastward gradually and deposited on the delta of the Don, and the delta was then raised above the surface of the water and extended far beyond its original limits. While the writer agrees in the main with this opinion, he is inclined to attribute to the Don and its delta a very minor importance.

FIGURE 1.—*Toronto Island, 1880*

City Engineer's Survey

The Don, the Humber, the Rouge, and a number of other streams in the district have cut wide, deep valleys in the glacial debris back of the lake shore and have undoubtedly brought large quantities of material down to the shore. A very considerable portion of this erosion took place not only prior to the building of the peninsula, but also prior to the formation of the present lake. Evidence of this is found in the fact that east of Toronto there are a number of valleys which show mature development and grading accordant with abandoned lake levels below the Iroquois but above the present lake level, and more recent ad-

[2] Proceedings of the Canadian Institute, vol. ii, 1853-1854, pp. 105-107 and 223-230.

TORONTO ISLAND, 1793

justments to the present water level. Both the Rouge and the Humber have also excavated larger and broader valleys than the Don, and in practically the same kinds of material, but have built no appreciable deltas at their discharges. It must, however, be remembered that in distributing stream waste which is discharged into the lake the waves will distribute a considerable portion, consisting largely of the coarser debris along the shores; a smaller portion of the coarse material and almost all of the fine will be carried out and deposited in deeper water. Waste deposited below wave base would gradually accumulate in front of the mouths of these streams faster than elsewhere and a subaqueous platform would gradually be built. This platform would be the initial feature for the building up of a delta in later stages of the lake's history, had it happened that the supply of waste brought by the streams was greater than the shore processes were able successfully to distribute. This platform must also have hastened the rate at which the spit, once started, could have been built up, since it would reduce the amount of filling that otherwise the shore processes would have to perform.

Lake Ontario stood at its present level long enough prior to the formation of Toronto island to cut a sea-cliff along the shore that now forms the mainland adjacent to the harbor. The old bench line can be traced for some distance east of the Don, but opposite the eastern end of Ashbridge bay, if the old abandoned beach exists, it is not readily distinguishable. There is enough of the old beach discernible to show that Lake Ontario waves were once actively cutting at the Don mouth, from which it is inferred that at that time the Don delta was not encroaching on the lake shore.

Coming west from Scarboro along the lake shore, one readily notes that there is a rather obtuse angle between the shoreline in front of the bluffs and that of the old beach back of Ashbridge bay and Toronto harbor. An examination of the present shore will show several other places where similar abrupt changes in the direction of the shoreline occur. One of the most salient of these points is Raby head, near Port Darlington. On a number of occasions, when strong storms were blowing from the southwest, the writer has observed the waters of the longshore current moving eastward along the coast and discharging out into the clear waters of the lake off Raby head. The discolored water, which marked the course of the current, could readily be seen for as much as 3 miles east of the head, lying probably about 2 miles offshore, with clear blue water between it and the mainland. At Raby head at the present time no prominent bar has been built to reach above water level and the soundings available are not detailed enough to show that a bar exists,

though it is extremely probable that one is being built. The nature and persistence of the discharge, however, offers a suggestion as to the results that might be brought about were a large amount of waste supplied to the longshore current before it passes out into deeper waters.

At Scarboro and Toronto the strongest waves and associated longshore current would come from the east and southeast in former times as now. Because of the marked change in the trend of the coastline, the longshore westbound current would tend to discharge out into the lake at the point where the relatively abrupt change in the direction of the shoreline took place. The cliffs at Scarboro would supply an exceptional amount of loose debris, much more than is found anywhere else along the north shore. The result would be the construction of a flying spit from Scarboro waste reaching out into the lake from the point of discharge of the shore current. This spit would gradually increase in length and also tend to broaden. In time it would protect the land adjacent to the mouth of the Don from the eastern storms. Such storms as came from the west would not only be weaker agents of shore process, but would tend to force the debris which the Don was discharging into the lake back into the bay between the flying spit and the shore. In the early history of the lakes and of the bar it seems probable that the greater portion of the debris from the Don, like that from all the other streams up to the present time, was distributed along the shores by the shore processes, and that no distinctive delta was built up. In later times the protection afforded by the young Scarboro spit guarded the mouth of the Don from the master storms, and forthwith it began to build up a delta and to aid in the filling of what is now Ashbridge bay during the course of the delta formation. The westward progress of the spit was, however, far more rapid than the Don filling, so that in time the portion that now forms Toronto harbor was built west of the Don mouth.

At first the bar would be narrow and ridge-like, but as the apex advanced into deeper water its progress westward would be slower, giving time and opportunity for storms from other than the dominant direction to variously modify its apex. The general history of all such spits seems to be that when they reach deeper water the outer end shall be turned shoreward by waves and currents from deeper water offshore. The combined action of forward building and shoreward spreading lead, in this as in other cases, to the broadening and hooking of the free end of the spit, and incidentally to the inclosing of a number of lagoons between minor bars built at successive intervals, according as the longshore or transverse processes were the more active.

Sand dunes at local points.—An incidental feature associated with the formation of sand beaches and barriers at the eastern end of the lake is the occurrence of several series of sand dunes at the backs of several of the beaches. These dunes are built by sand blown shoreward from the gently sloping beaches by the stronger winds and gathered in drift-like waves or ridges some few yards behind the wave-swept zone. Low dunes only 5 or 6 feet in height occur on the mainland shore just west of the Presque Isle tombolo. A belt of dune sand about a quarter of a mile wide, some of the dunes being nearly 50 feet in height, has been noted as occurring on the neck of the Presque Isle tombolo. Small dunes, the highest about 25 feet above lake level, occur near the south end of the sand spit which incloses Weller bay. Similar dunes, but larger, are found on the bar—beaches which inclose West and East lakes south of Wellington. The highest of these dunes, at the southwest end of East lake, has an elevation above lake level of about 100 feet. About 45 years ago the protecting growth of scrub oak, red cedar, white cedar, white pine, and various bushes was partially or wholly removed. Since that time the dunes have moved landward about one-quarter of a mile. They are now slowly encroaching upon good farm land at the southeast end of the lake. Some futile attempts seem to have been made to stop the encroachment by planting willows and white cedar. The latter are all dead and the former are not thriving greatly. The tops of cedars and some few pines, which grew upon the land behind the dune belt in the early days, are now just visible above the sand.

A row of low dunes, more or less covered with a growth of white and red cedars, basswood, and oak, occurs along the bars built across the several bays at the east end of the lake.

LAKE ERIE

General character of the Lake Erie shore.—The Lake Erie shore differs from that of lake Ontario mainly in the character of its beaches, which are usually very broad and of a low angular slope. Nearly the entire shoreline of the lake on the north side is bordered by bluffs of loose glacial waste, and the amount of shore waste is much greater than on the other lake. The initial topographical forms were almost wholly glacial, and even in its early stages the shoreline must have been relatively simpler than that of Ontario. Bay-bars which can be attributed to the direct action of the waves are not present. There are a few large bays cut off from the main lake by barrier beaches, such as East and West harbors, between Catawaba island and Sandusky. A number of smaller barrier beaches occur along both the north and the south shores of the lake. In every instance the waste composing them seems to have been

FIGURE 2.—Long Point Spit

derived largely from the adjacent cliffs; the beaches were built up by the action of the surf and the associated longshore current.

Excellent examples of the flying spit are found at Erie harbor (Presque isle), Sandusky harbor (Cedar point), Maumee bay (Grassy point), and at Long point. The cuspate foreland is represented by Turkey point, Point aux Pines at Rondeau, point Pelee, Cedar point on Maumee bay, and by several minor points. In the present article the descriptions are limited to the most important of these.

Special features: Long point.—Long point is a low lying flying spit composed of sands and gravel. The apex of the point lies about 21 miles east of the place of junction between the bar and the mainland. At its widest place it is 3½ miles across. The eastern or free end lies in lake Erie nearly south of Port Dover and 18 miles from shore. The lakeward side of the spit is a continuous beach of gravel and sand. The inner or bay side is covered by extensive marshes. Two prominent forelands, Pottohawk point and Bluff point, project from the inner side out into Long Point bay. These points were probably formed during the earlier history of the spit and indicate that during the earlier stages of its growth the point was hooked inward and progress eastward was retarded. At the present time the northeast facing portions of the inner side of the Long point are exposed to the action of waves from Long Point bay. East of Pottohawk point the shore of the spit presents a narrow beach; at Bluff point the lake charts show that a local shoal has been formed, extending out into the bay toward the northwest. Blown sand forms low ridges over the interior of the island. Most of the low dunes are covered either with a thick growth of grasses and sedges or with trees.

The Long Point beach starts to swing away from the mainland about 1 mile east of the west town line of Walsingham township. From this place an old line of sea-cliffs can be readily traced to Port Rowan, and thence passing back of Turkey point to the main shore near Normandale. Between the present beach and the old shoreline, from the Walsingham town line to Port Rowan, there is an extensive swamp area partly overgrown with timber. For about 4 miles east of Port Rowan the old sea-cliffs are separated from the present bay only by a narrow strip of swampy shore. The cutting on the cliffs is comparatively recent, and the cliff faces are much fresher than along the swamps, both east and west. From the west side of Turkey point to near Normandale the old cliff line forms the base of Turkey point. Between the foot of the cliff and the beach, on the point, there are wide swamp areas, open toward the west to Long Point bay.

At one time the bar which connects the main portion of Long point with the mainland lay much farther out in the lake than at present, but in recent years it has been cut back. This is well shown by the numerous old stumps and roots which occur at the water line about 2 miles west of the Walsingham town line.

West of Long point the sea-cliffs consist of a brown boulder-clay overlain with stratified sands and gravels. Their height varies from about 50 to over 100 feet within the first 10 miles, and farther west they are still higher. A study of the map of the lake shore shows a very marked change in the trend of the coastline where the connecting bar leaves the main shore.

Long point is considered by the writer to have been constructed by the joint action of the surf and the longshore currents moving debris—waste derived from the cliffs or supplied to the shore by streams from the interior—eastward along the shore probably from as far west as point Talbot. At Walsingham the change in the trend of the shoreline caused the longshore currents to discharge lakeward instead of following the shore farther. Gradually the great mass of waste contributed by the cliffs accumulated in the long, low, sandy ridge that now constitutes the point. During the later stages of its growth the materials of which it is built up must have been frequently rearranged by the direct action of the waves.

On the mainland, projecting out into Long Point bay 6 miles east of Port Rowan, is the cuspate foreland, Turkey point. This foreland is bordered by a fresh beach on its southeast side, fronting toward the open lake, but the western side is low, swampy ground. The waste of which the point is built, at least in the later stages of its growth, has come along the shore from the east. Several successively abandoned beach lines are to be noted back of the present beach, marking earlier stages in the growth of the point. The old line of sea-cliffs cut in boulder till rises about 40 feet above the general level of the point. A small creek flows into one of the swamps back of the point not far from the middle of the base. This creek has cut a deep valley in the glacial deposits, but it has built only a small, flat, alluvial cone in front of the old cliff and resting on the old beach. This leads to the inference that the greater portion of the dissection of this stream valley took place before Turkey point had closed direct communication with the lake, for the size of the alluvial fan is altogether disproportionate to the amount of valley dissection.

Point aux Pines, or Rondeau.—Following the line of sea-cliffs west from point Talbot to the east line of Harwich, we find that near the base of Point aux Pines, or, as it is sometimes called, Rondeau point,

the cliffs become very low, and that behind the point they are not distinguishable. Back of Rondeau harbor, across the front of Harwich township, the land slopes gradually down to lake level, and a growth of reeds and sedges near the shores of the harbor obscures any traces of the abandoned earlier shoreline of the lake. About one mile east of the west town line, where the western flying spit that incloses the harbor leaves the main shore, low sea-cliffs again appear. The form of the shore, as it is at present, shows that probably in the early history of the present lake two low flying spits must have been formed about 5 miles apart, one of them with the free end pointing east, relatively small, the other with the free

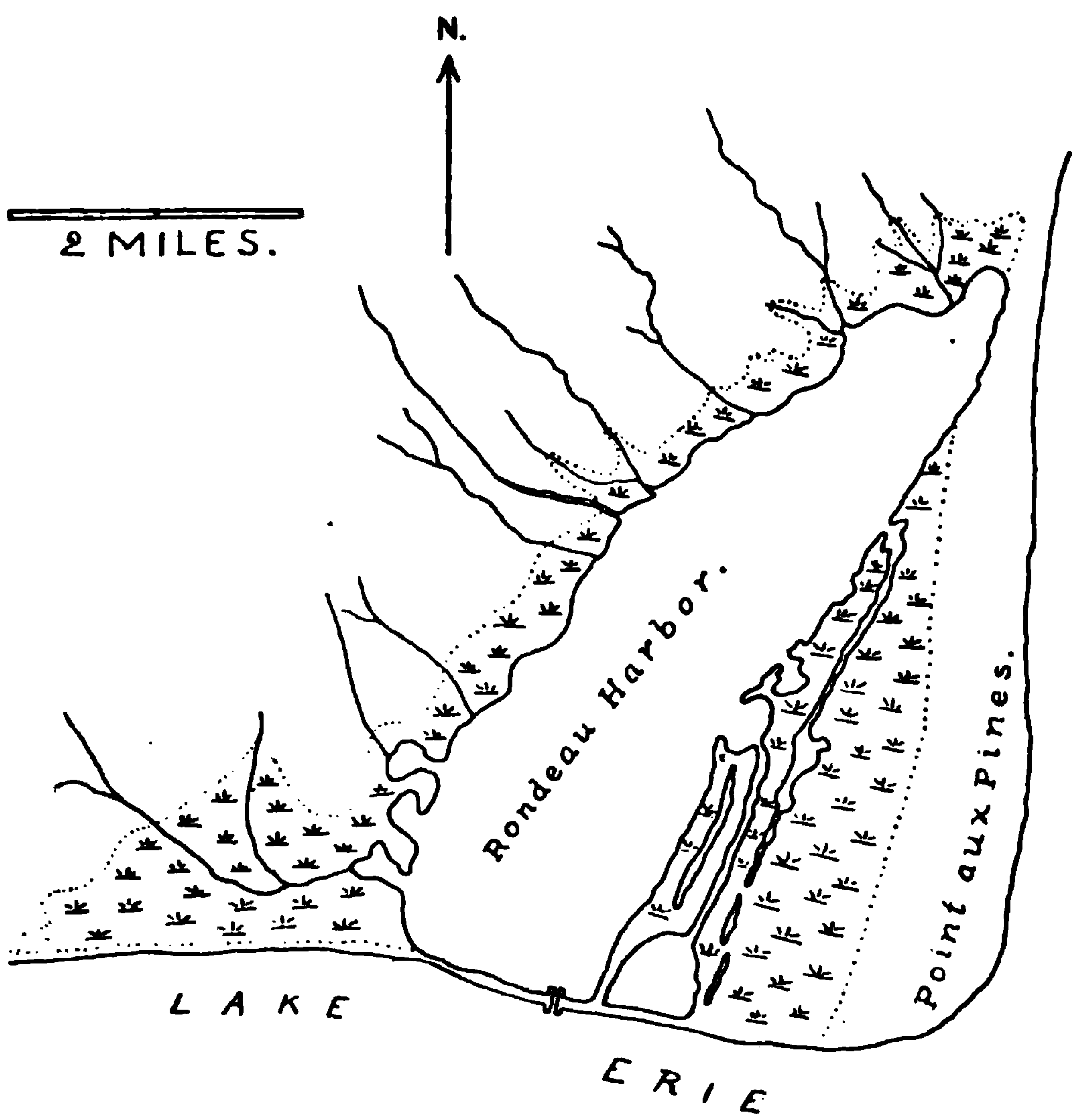

FIGURE 3.—*Point aux Pines, Lake Erie*

end reaching out toward the south, relatively larger and more actively aggrading. The former probably swung away from the old shoreline near the point where Rondeau village now stands, and was built of waste brought from the west; the latter probably left the main shore at or near where the east town line of Harwich reaches it. The supply of waste from the northeast would be the larger, and it would be moved along the shore to its place of deposition much faster than that from the west.

At the present time the western spit is represented by a narrow bar which joins the broad southern portion of Point aux Pines to the main-

land on the west. This bar is from two to three hundred yards in width and rises about 15 feet above lake level. It is composed of sand and gravel. The outer beach is wave swept and steeper than the inner slope, which is grown over with grasses. The length of the bar is about 2 miles. Between the bar and the old shore are extensive swamps containing much peat. Soundings made to estimate the quantity of peat present have shown the existence of other parallel bars with deep (15 feet) beds of peat between them. The existence of these bars inside the present bar shows that during the growth of the point the place of attachment of the western tie bar has gradually shifted west as the growth of the point progressed.

The eastern or main portion of Point aux Pines consists wholly of sand and gravel. On its lakeward side it is bordered by the usual wide wave-swept graded beach. The inner side is bordered by low, swampy areas. The progressive growth of the bar has gradually widened it at the south end, so that it now has a width of about 2½ miles 4 miles south of where its shore end joins the mainland. Old dune lines and abandoned beach lines can be readily located, particularly near the outer end of the spit. Low dunes are also to be seen near the attached end of the spit formed by sand which has been blown back from the present beach. The greater portion of the point is timbered with white pine.

Point Pelee.—Point Pelee is a triangular cuspate foreland with its apex to the south. The base is about 5 miles across and the point projects southward about 10 miles. Only the outer 4 miles of the apex of the point have been built by the present lake. The inner portion, now a large swamp area, cut off from the lake on either side by high beach ridges, is covered with a soil cap of black loam varying in thickness from 1 to about 4 feet; below the loam is a heavy bluish clay which carries a few boulders and some fine gravel and is probably of glacial origin.

The point differs from all other similar features on the lake, except Point aux Pines, in that no distinguishable well marked abandoned shoreline accordant with present lake level can be traced across its base. There is an old shoreline, standing approximately 8 feet above lake level, which joins the present sea-cliffs both east and west of the point, but it obviously belongs to an earlier stage in the lake's history.

Topographically this portion of Essex county is a plain with a gently undulating surface. The initial point was formed by a light swell on the surface of the plain, which caused the lake shore contour line to loop southward, forming a low rounded point. This nearly flat point would be exposed to the direct attack of lake waves, and in this attack the waves would tend to cut the margin of the new point down to wave base and at

the same time to construct a bar either on the low shore in front of the place of attack or some little distance offshore. From the character of the shores these bars would be closely associated with or joined to the mainland beach line, and longshore transportation process would bring much waste from east and west, particularly the former. The abrupt

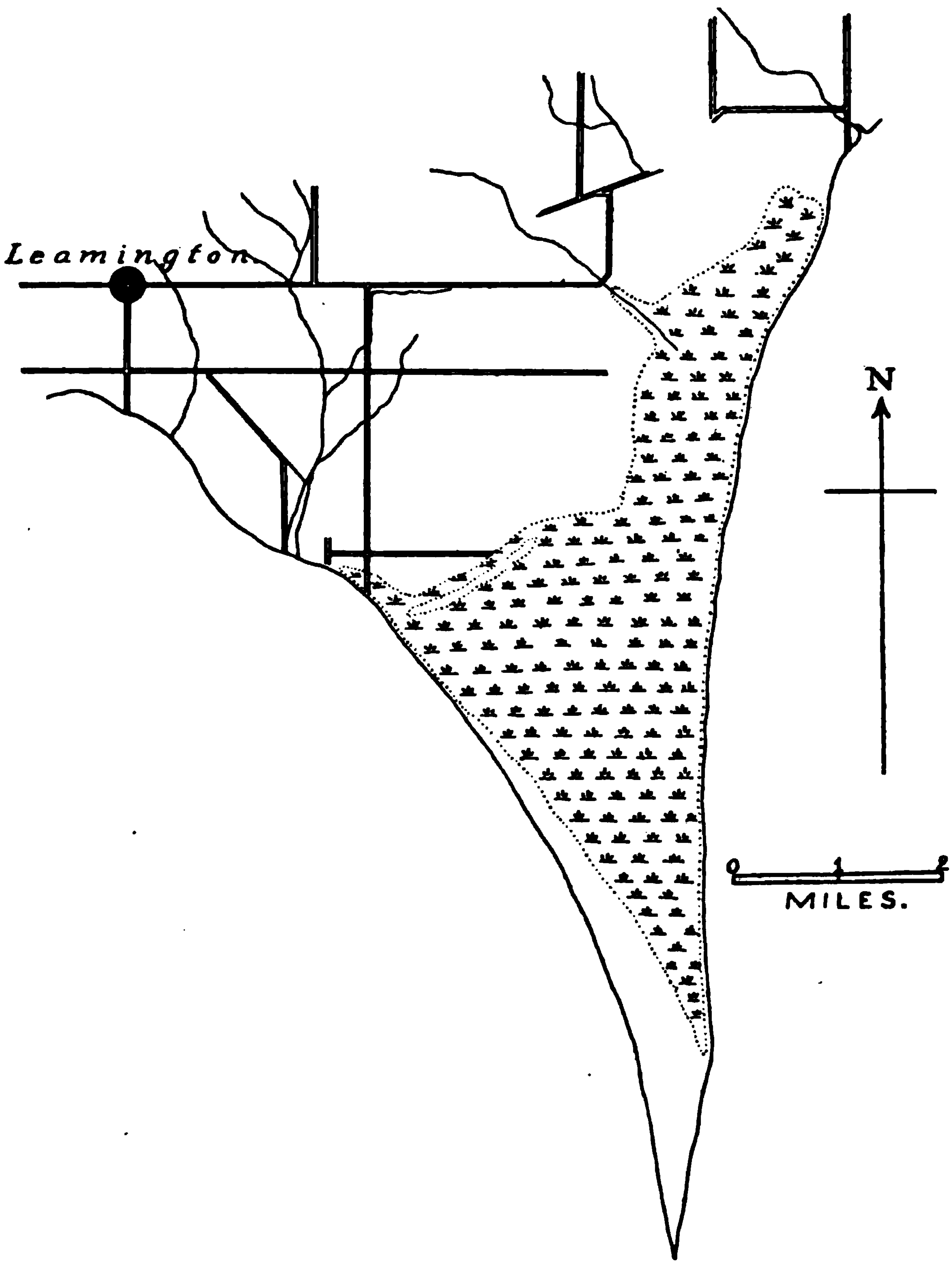

FIGURE 4.—*Point Pelée, Lake Erie*

changes in the trends of the shoreline would cause an accumulation of waste at the point. During later stages the earlier offshore bars, if such existed, would be thrown back upon the main portion of the point. At the present time the portion of the point between the barrier beaches is

free from sands and gravels, while both east and west they make up the greater portion of the waste supplied by the present sea-cliffs. The present barriers and the outer 4 miles of the point are composed almost wholly of materials derived from the cliffs east and west. Hence, while in the initial stages the waves would tend to build barriers by their own undercutting, the point as at present constituted is formed practically altogether of materials brought hither by longshore processes.

On the west side of the point for the first 2 miles offshore the barrier ridge is only about 125 feet in width; then it gradually widens. About 4 miles from the apex of the point the beach deposits on east and west join and have a width of about 2 miles. Along the west shore at the present time the beach is steep and is covered with grass almost to the water's edge. The greater portion of the bar is covered with a thick growth of timber—red cedar, white pine, white cedar, oak, and an occasional walnut or plane tree. A sand dune belt occurs along the middle portion of the west bar, most of which is stationary. During recent years there has been a good deal of undercutting on the west bar about 4 miles back from the end of the point.

The eastern shore of the point consists largely of very coarse gravels and is built up fully 20 feet above the lake level, or more than twice as high as the west beach. The barrier beach is wider than on the west and active construction work is still in progress. The difference between the east and west beaches is a very striking evidence of the strength and character of the shore processes acting on the two sides of the point, the east being exposed to the full sweep of the waves from the east, while the west is relatively well protected from large storm waves.

Presque Isle point, or Erie harbor.—On the south shore of the lake, directly opposite Long point, lies Presque Isle, inclosing a lagoon that now constitutes Erie harbor. East and west of Erie the sea-cliffs lie immediately back of the beach line. A few feet at the base of the cliff is usually rock. This is overlain in turn by glacial till, stratified clay, and sand and gravels. The cliffs vary in height from 40 to about 90 feet. The line of cliffs passes along the mainland south of Erie harbor.

The point itself consists of sands and gravels still retaining many traces of the earlier beach lines. The present beach is broad and rises to about 8 feet above lake level. Behind the beach are low ridges of windblown sand rising 6 or 8 feet higher. The hooked spit is joined to the mainland by a narrow sand-neck. At the present time the supply of materials from the west seems to have been so reduced that erosion is narrowing and reconstructing the neck.

The form of the point and its position with respect to the waves of

maximum efficiency on this portion of the south shore show that it has been built up largely by materials brought from the west. On the east much waste has accumulated on the mainland shore in the lee of the spit,

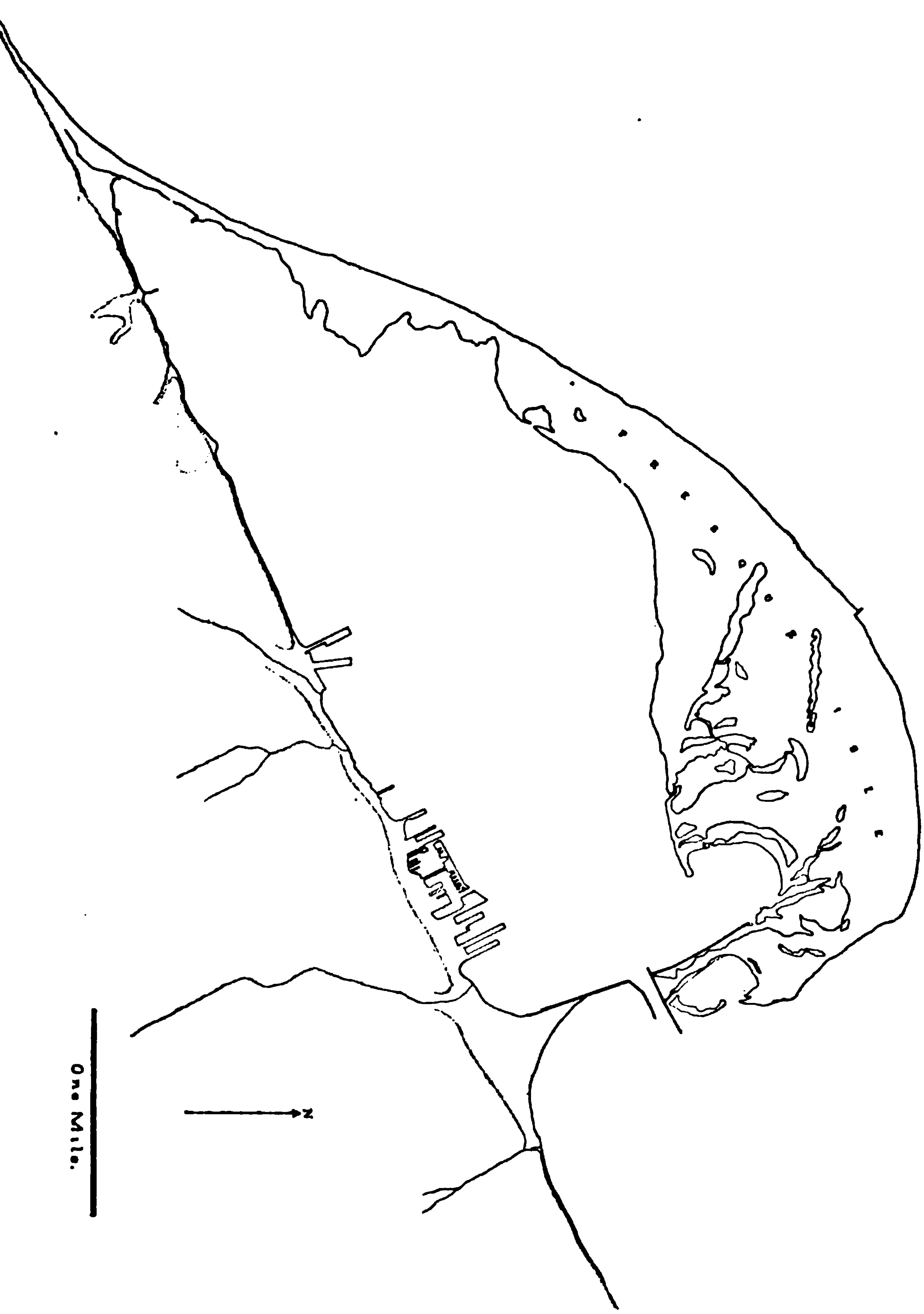

FIGURE 5.—*Presque Isle Spit, Erie Harbor, Lake Erie*

forming a small cuspate foreland. The material in this foreland was derived largely from the cliffs along the shore to the east.

The reason why the flying spit was located just at this place on the south shore of the lake it is a little difficult to find. There is a slight change in the trend of the shoreline at the place where the barrier leaves the mainland, but there are other localities east of this where present conditions seem equally favorable and where no spit has been formed. The amount of rock exposed at the bases of the cliffs east of this is greater than here and the supply of waste would be less than at Erie.

Sand dunes.—On nearly all the spits and forelands on the lake, belts of low dunes have been built behind the beaches. In the majority of cases these dunes are now stationary because of the presence of growing trees.

Particularly along the north shore of the lake, however, there is another type of dune that is of economic importance. Most of the sea-cliffs on the north shore expose the raw edges of extensive beds of sand containing perhaps a little gravel. At the bases of these cliffs the beach usually consists largely of sand and is usually wide and of a low angle of slope. Strong winds blowing shoreward create an updraft in front of the cliffs. The upper air above the level of the crests of the cliffs continues to move forward approximately in its original horizontal direction. At or near the crest of the cliff, however, the updraft intercepts the horizontally moving layers of air, and strong vortical whirls rotating inward are produced at the edge of the cliffs. Where the slope of the cliff face is not too steep, the updraft carries great quantities of sand before it, and the vortical whirl at the edge of the crest causes it to accumulate just behind the crest. In this manner extensive dunes have been built up close to the crests of some of the sea-cliffs.

Numerous small, low dunes of this type (20 to 80 feet high) occur along the shore east of Port Rowan, notably near Port Colborne. Along the cliffs west of Port Rowan there is also an extensive dune belt. In Houghton township about 11½ miles west of Port Rowan some very large dunes occur. One of these rises about 120 feet above the edge of the cliff and about 200 feet above the water. The north and northeast face of the dune presents an even slope from base to summit and was extremely difficult to ascend, as the sand has assumed the steepest angle of repose and moves very easily. The crest line was very sharply marked. At the crest the sand was quite moist and the adhesion was strong enough to permit of the formation of overhanging edges in many places exactly similar to the crest edges of a snowdrift. A few feet from the crest toward the lake the moist sand was covered by about three-quarters of an inch of dry sand. On the lee side, a few feet below the crest, the dry sand was about three inches thick. Had it not been for the adhesion of the moist underlayers it would have been almost impossible to ascend the

dune from the land side. On the lake side some distance below the crest the dry sand had all been blown off and the edges of moist layers projected. This dune is very old, as is evidenced by old tree trunks, now much carved by blowing sand, which occur on its back slope. It is now advancing very slowly inland on an adjacent piece of woodland.

West of here, toward Port Stanley, other, but usually smaller, dunes occur along the edges of the cliffs.

Geologic Process on the Shores

MOVEMENTS OF THE LAKE WATERS

The several forms of movement.—While the existence of periodic movements of the waters of the Great lakes corresponding to the tides are known, the amount of movement is insignificant. On all bodies of water exposed to the action of winds, three distinct types of movement are developed in addition to the tidal movements—the seiche, the currents, and the waves. The current movement may also be developed directly or indirectly by gravity. All movement of the shore materials, on a significantly large scale at least, must be through the action of one or more of these movements, either acting separately or in conjunction.

The seiche.—The amplitude of the seiche oscillation is directly dependent on the wind velocity and persistence in a constant or nearly constant direction. As an agent of transportation when acting directly, it is practically powerless. Acting indirectly through the operation of currents passing through narrow channels, it may possibly be able to shift some very fine materials, such as clay held in suspension. Under very favorable circumstances, in the Murray canal, where a relatively very powerful seiche current is generated, it was not found strong enough to transport for more than a few feet even very fine silt when mechanically stirred up from the bottom. Normally the only material moved by it is floating debris. At the east and west ends of the two lakes the periodic raising of the water during storms greatly broadens the portion of the shore belt within the immediate zone of action of the storm waves.

Currents.—In the report by Mr M. H. Harrington, issued by the United States Weather Bureau,[3] the currents of the Great lakes are grouped under four heads: The body currents, a surface current due to the prevailing winds, the return currents, and surf motion. The body currents and the return currents may be regarded as constant. With these should be associated the locally constant currents found at the points of inflow and outflow of the main streams of the lake system—the Detroit,

[3] Currents of the Great lakes. Bulletin B, U. S. Weather Bureau, 1894.

the Niagara, and the Saint Lawrence rivers. At these points there is a small but constant current, really a portion of the body current, but much more readily noted than the body current of the main lake. These local currents are too weak to be active transporting agents. In the case of the Detroit river the occurrence of delta deposits at its mouth, although in part undoubtedly due to wave action and other local causes, may be due to the river's ability to transport materials supplied by the waves on lake Saint Clair, the materials being carried down the channel of the river by the current to lake Erie and being deposited in the latter lake as soon as the current is arrested by the lake waters. In the case of the Niagara river the discoloration of the water shows that a small amount of material in a very fine state of division is carried out into lake Ontario.

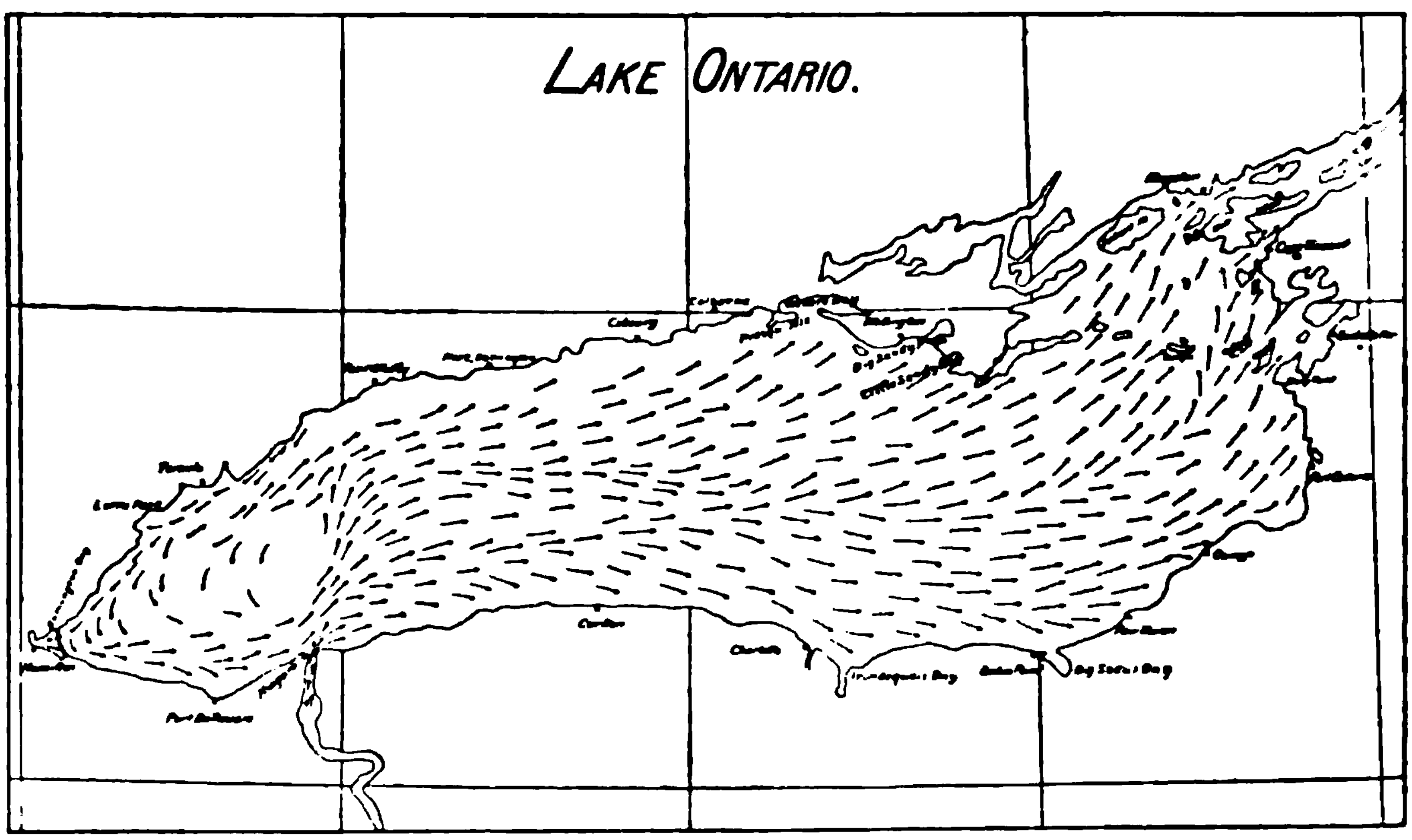

FIGURE 6.—*Drift Currents in Lake Ontario*

Two miles off the mouth of the river the coloration has disappeared and the current has become merged with the general drift of the surface waters of the lake. It has also been noted that the outer portion of this current in lake Ontario is shifted by the winds. The waters of the Saint Lawrence where it leaves the lake are clear and practically free from sediment.

In lakes Erie and Ontario the general study which has been made by the officials of the United States Weather Bureau has shown the existence of a slow general set of the mass of the water toward the outlets. Where, by the action of the wind, surface currents have driven more water to the eastward of the lakes than can well pass through the discharge, there must be more or less of a return current. In the case of these two lakes

no return current so well marked as in the other lakes of the Great Lakes system has been found. The probability seems to be that in part it breaks up into smaller whirls along the great pockets of the coast on either side of the general current, and that a considerable body of water is returned as an undercurrent. The general east flowing current is very slight, probably never exceeding 12 miles per day, more frequently being much less than this. The currents of the general circulation and the return currents are too feeble to transport even the finest sand which occurs along the beaches. They must, however, assist in the distribution of the finest silts and clays over the bottoms of the lakes.

At points along the shores of the lakes, streams other than the main rivers of the system enter, and their currents may at times, especially during the period of spring floods, affect the waters of the lakes for a short distance from the shore. At this time one can often see the discolored waters flowing through the clear lake waters for a mile or more, rarely over 2 miles from the mouth of the discharging stream. This discoloration is produced by the silts in suspension, but even these are quickly deposited in the relatively more quiet waters of the lakes. Except in the immediate vicinity of the mouths of the streams in question, these currents have no effect in modifying the lake shores. The direction that they turn in flowing through the lake waters, except for the first few yards of their course after leaving their outlets, is determined wholly by the direction the lake waters at their point of discharge happen to be moving at the time.

With regard to the surface currents produced by the prevailing winds, their general direction is the same as that of the wind with which they are associated. A study of the prevailing winds for the lake stations, made by the officials of the Weather Bureau and covering a period of seventeen years, shows that there were on the average 66 per cent of westerly winds for the whole year. For the months from May to September 56 per cent were from a westerly direction. For the same period of time a study of the resultant wind directions shows that in 183 out of 204 monthly values and in all the annual values the resultant is westerly.

The occurrence of undercurrents in a direction contrary to that of the surface current or of the prevailing wind is a common feature. Mr L. J. Clarke[4] found some interesting examples of these currents off Toronto when making investigations of the lake currents in that vicinity. Mr Clarke also mentions that fishermen at Niagara, New York, found

[4] Transactions of the Canadian Institute, vol. ii, 1890, pp. 154-157, and vol. iii, 1891, pp. 275-281.

that when they had their nets set in deep water during the prevalence of strong easterly winds they would find in drawing the nets that any floating submerged leaves or weeds would be caught on the opposite side of the net, showing that the undercurrent was from the west. This would indicate that the waters, being driven to the west, pile up at Burlington beach, and the head of water thus raised forces a portion of the water back as an undercurrent. The seiche oscillations on the lakes must tend to generate local undercurrents at the ends of the lakes whenever the water rises above the mean level.

Out on the open lake the transitory movement of the water before the wind takes the form of a drift, and because of the prevalence of westerly winds this drift is most frequently identified with the easterly

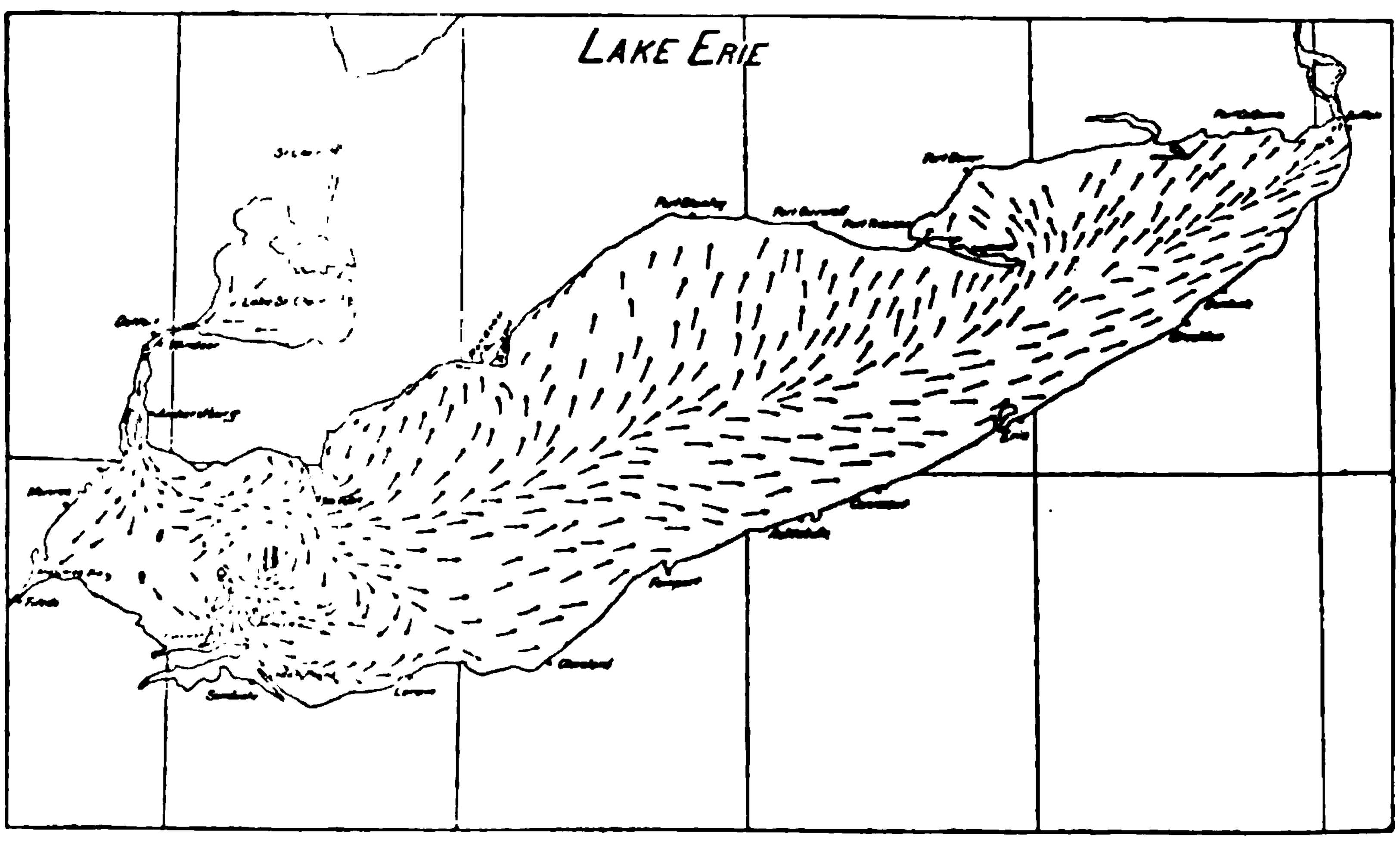

FIGURE 7.—*Drift Currents in Lake Erie*

flowing body currents of the lakes. The drift currents vary their direction with the wind that causes them, usually starting a short interval after the wind has commenced to blow and continuing for some time, often several hours and occasionally several days, after the winds that caused them have ceased. Where this drifting surface water impinges on a shore a longshore current is developed, the direction of the current being dependent on the angle at which the drift impinges on the shoreline. These currents, which for convenience may be designated wind currents, are seen during wind storms and reach their maximum velocity at times of the strongest storms. They are so intimately connected with wave and surf movements that both must be considered together. It is when they act in conjunction that active erosion, transportation, and deposition take place.

Waves.—The same wind that generates a surface drift that becomes a longshore current where it impinges on the shore also develops waves. At a few points the water of the wave may roll up on the beach at the shoreline and run directly back again, but only at those points where the shoreline is parallel to the wave front. On the Great lakes, where the shorelines sweep in great open curves, with chords often from 4 to 8 miles in extent, the wave front very frequently advances at such an angle to the shoreline that the wave rolls up the beach obliquely. Where this happens the water never returns by the same path that it came, but runs off obliquely; so that material on the beach tends to travel along the shore by a zigzag path, the angle at which the wave strikes the shore determining the angle between any two limbs of this path of travel.[5]

Interrelations, waves, and currents.—Along a stretch of lake shore where the waves are impinging obliquely and where a number are always breaking at once, the tendency will be for the waves themselves to generate a longshore current flowing in the direction in which the bisector of the acute angle between the wave front and the shoreline points. This wave-generated current is always accordant with the longshore drift current caused by the same wind, and as they operate together in shore transportation they may be referred to simply as the longshore current.

After the wind which has started the waves and currents has ceased to blow, the swells still continue for some time, and even after the swells have ceased to be perceptible the longshore wind current remains quite strong, the momentum which the water acquired during the period of storm not being expended for some time after the storm has ceased. It not infrequently happens that a new wind from a different quarter may spring up and start to generate a current in an opposite direction. This affects the surface waters first, while the lower water still retains the motion in the original direction; also the water immediately along the shore is affected to the bottom some time before the deeper water offshore has had its momentum destroyed and its direction of flow changed.

TRANSPORTATION DURING STORMS BY WAVE-GENERATED LONGSHORE CURRENTS

In the shifting of materials along the shore the only effective agents of transportation are the wave-generated longshore currents and the waves associated with them. Transportation of all but the finest materials ceases as soon as the swells disappear, and is at its maximum at the time the waves are largest. The longshore currents are not of themselves

[5] See discussion by Sir Sanford Fleming: "Toronto harbor, its formation and preservation." Canadian Journal, vol. ii, 1853-1854, pp. 105-107 and 223-230.

strong enough to hold even fine sands in suspension for any length of time—a fact which may be readily ascertained by experiment, or as is shown by the rapidity with which the water in the shore zone clears as soon as the waves cease. During the late autumn, following the autumn gales, and during early spring, following the winter storms, there is a belt of water along the shore in which there is a great deal of fine clay in suspension. In Ontario at times this belt is as much as a mile or more in width; in Erie, which is much the shallower of the two lakes, it may be 2 or 3 miles wide. This suspended clay is carried for some time by the longshore currents and also by the currents of the general circulation; but transportation of the sands and all coarse materials on and along the shores ceases as soon as the swells stop. The coarse materials—boulders, cobbles, and pebbles—are shifted almost wholly by the waves, the smaller gravel and the sand by both waves and currents, the finer clays largely by the currents. During a period of heavy storms a longshore current may acquire a velocity as much as 4 miles an hour.

THE SUPPLY OF MATERIALS

CHARACTER OF THE MATERIALS

The materials in general.—The materials found on the shore and adjacent to it, which have been distributed there by the shore processes, are fine clays and silts, sands and gravels, cobbles, and boulders. The clays and silts in large part are derived from similar materials *in situ* and are brought to the shores by various processes; in small part they are produced at the shore by the grinding of the coarser materials upon one another and on the bedrock in the process of transportation. The sands are derived almost wholly from sands of glacial origin. The gravels and cobbles come from beds of till in large part; along those portions of the shore where there are bedrock exposures often almost all of them are derived from the bedrock *in situ.* Generally there is a slight admixture of material of glacial origin. The boulders and large blocks are usually of glacial origin, though here and there one may note blocks of the adjacent bedrock only shifted a short distance from its source.

Bedrock.—The shores of the lakes are rock-bound only in a few places. The north shore of lake Ontario westward as far as Presque Isle is largely Trenton limestone. Between this point and the mouth of the Humber, west of Toronto, there are only three small areas in which rock (Trenton limestone) is exposed at the shoreline. West of the Humber, Lorraine shales are exposed for a short distance, and then there is an interval of several miles to a point just west of Lorne Park

where shales and sandstones of the Medina border the shore. On the south side there are frequent exposures of the Medina strata at the west end and for some distance east of the mouth of the Niagara river. The intervening shore as far east as Sodus point is not known to the writer in detail, but it is understood to be made up largely of glacial materials overlying bedrock which usually outcrops below water level. East of Sodus point and as far as the Saint Lawrence there are a number of places where limestone ridges extend out into the lake as points or islands. Except in the two localities on the north shore at the east between the Saint Lawrence and Presque Isle, and at the west between Lorne Park and Burlington, the rock exposures are very small and are usually overlain by a considerable amount of glacial debris, which supplies the great bulk of the shore materials on these shores.

On lake Erie the rock exposures on the north shore are fewer in number than on lake Ontario, and the glacial and lacustrine deposits overlying the rocks are thicker. The principal rock exposures occur near the east end of the lake, east of Normandale, where low rocky points are the rule. At the west end of the lake and on the islands south and west of point Pelee, rock outcrops from beneath the loose glacial debris. Along the south shore bedrock underlying glacial deposits is frequently noted at the base of the line of sea-cliffs. The material supplied to the waves from the bedrock is on the whole very small in quantity.

Glacial materials, till, interglacial sands, and gravels.—By far the larger portion of the loose materials which are operated on by the shore processes of both lakes are of glacial origin—till derived either from drumlins or moraines, and sands and gravels derived from kames, eskers, sand plains, or more frequently from the lacustrine deposits of the interglacial epochs.

Lacustrine materials—secondary.—Lacustrine materials of post-glacial date, derived from the earlier glacial deposits, are also a minor source of shore materials; but it is usually impossible to distinguish them from the similar deposits from which they were derived, and, so far as the study of the processes on the shore are concerned, it is unnecessary to make any distinction between them and the earlier glacial materials.

SOURCE OF THE SHORE DEBRIS

The materials, whatever their type, are brought within the range of the shore processes by various agencies.

The waves cut out much waste by direct action on drumlins and other topographic forms of glacial origin. Indirectly they are aided by numerous other agencies, animate and inanimate.

Where there are sand beds of interglacial origin underlying till or

stratified clays impervious to moisture, erosion is aided, and indeed hastened, by the action of springs. Particularly during the winter season, when the faces of the wave-cut cliffs are protected from the direct action of the waves by shore ice, and when the flowage of ground water through the sand beds is more or less retarded if not stopped, water tends to accumulate in these beds along the base of the cliffs. In the early spring, when the frost loosens, this accumulation of water carries out considerable quantities of sand, particularly where it is fine textured, undermining the overlying materials. The water also acts more or less as a lubricant; so that, once the undermined materials start to slip, often large blocks move down the faces of the cliffs lakeward and are brought within the reach of the waves. The quantity of material thus brought to the wave zone is very large.

In the process of cliff formation by spring undermining, in a number of places where interglacial sand, gravel, and clay beds with some interbedded layers of till occur, there are developed interesting amphitheater-like openings in the cliffs, which from their form and origin may be named "spring cirques." The undermining processes in these cases seem to have been most active at first in a lineal direction, possibly developing a subterranean channel along which the sand and water first flowed. Inland some little distance from the shore cliff this channel has widened, and in time, by the process of caving, a large amphitheater is opened behind the cliff, with narrow ridges on the shore side between the amphitheater and the shore. This type of cliff erosion is well shown on the Lake Ontario shore near Newcastle and again at the Scarboro bluffs. Similar forms are also found in the high cliffs on lake Erie west of Port Rowan.

The cliff erosion is greatly hastened by the burrowing of animals, particularly sand martins and kingfishers, and less frequently by groundhogs. The nests of the two birds mentioned are made at the back of a burrow, 3 to 6 feet in depth, always dug nearly horizontally backward into soft sand deposits. At times of excessive rains, or in the springtime, when the frost is passing out of the ground, these old burrows often act as channels through which water at first trickles, but which it gradually widens and deepens until the outlet becomes a well defined channel and the protecting sod cover above is undermined and ruptured.

During recent times the cliff erosion along the shores has been very materially hastened by human agencies. In a small way the opening of the nests of the birds before referred to, by predatory boys in search of eggs, gives rains early access to the burrows. The writer knows of at least one instance where an old kingfisher burrow has become a deep

FIGURE 1. ABANDONED SEA-CLIFF BEHIND TURKEY POINT

FIGURE 2. ALLUVIAL SAND CONE, SCARBORO (EARLY SPRING)

FIGURE 3.—CLAY SLIP AND ALLUVIAL CONES, SCARBORO (WINTER)

VIEWS ILLUSTRATING SHORELINE STUDIES

channel in the cliff, running back nearly 100 feet, and at the present time the cliff has retreated at least 6 feet since the burrow was opened out. The materials at this point happened to be hard glacial till. Had they been soft sand, the destruction in the time which has elapsed since the burrow was opened would have been much greater.

The farmers plowing their land close to the edge of the cliffs, particularly when the furrows are made at right angles to the shoreline, break the protecting vegetable covering and binding roots and open up just so many potential channels, this being particularly true if the soil is sandy. There are numerous instances to be seen along the shores of both lakes where deep notches have been cut in the cliffs and where channels run back inland, in some cases as much as half a mile, which have been started by carelessness or by ignorance in the matter of a proper method of plowing.

A considerable amount of material, particularly of the finer sorts, is brought down to the lake shore from the interior by the streams and rivers. In times past the amount must have been very large, if one may judge by the size and form of the valleys the tributary streams have carved in the glacial deposits across which they drain. At present during the greater portion of the year the amount of material transported is exceedingly small and the total amount contributed by the streams to the shore waste is, compared with that derived from the immediately adjacent land, relatively insignificant.

Distribution of the Materials on the Shores

The waste supplied to the shores from different sources is spread out in a nearly even sheet parallel to the shoreline; much of the finer materials are carried out rapidly to the deeper waters and there deposited, while the sands and coarser materials are shifted along the shore within the limits of the wave-swept zone. The active agency in this distribution is the waves and the longshore currents, which are always associated with them. Most of the active transportation takes place during the time of the greater storms; during a period of light winds only sands and finer gravels are moved. Probably the greatest amount of transportation is during the period of autumn storms, though a very considerable movement takes place also in the spring. During the summer months, except when there occurs an unusual and heavy storm, transportation is very slight. During the winter months, when the shores become lined with ice, often forming cliffs 6 to 15 feet in height and extending out into water about 4 and occasionally more feet in depth, transportation is at a minimum.

While the winter ice protects the shore for a time from the action of

waves and confines it to the portion of the wave zone beyond the ice-foot, still it facilitates shore erosion in another way. During warm days in winter, particularly in the case of cliffs facing south, local thawing takes place and produces small landslides. The material thus loosened slides down the cliff face upon the shore ice. During early spring, before the shore ice melts, this action is accentuated and local washouts often carry great quantities of waste out upon the ice. Then with the opening of the lake much of this ice, with its load of debris, is floated off by the waves and is transported a considerable distance before it melts and loses its load. In this way much coarse waste is being moved along the shore, and no inconsiderable portion must find its way out into the deeper waters of the lake, there to be deposited with the finer silts and clays.

Particularly during the early spring the waters of the lakes in a belt along the shore and for a mile or more in width assume a whitish appearance, owing to the fine materials suspended in the water, usually clay derived from the till along the shores. In the case of lake Erie, which is much shallower than lake Ontario, the suspended clay is always to be seen along the shore belt of water, but in Ontario the water usually clears in the late spring and remains clear until late in September. This finer material must be moved a considerable distance before being deposited, and comes within the zone of action of the body currents, as also does the floating ice and the materials it transports.

In the shifting of the materials along the shores of the lakes locally they are being moved now in one direction, now in the other, according to the wind direction. It is found, however, that a single great storm will undo the work of many previous gentler winds. A study of the transportation conditions along the shores of both lakes shows that two distinct resultant shifting movements may be recognized on each lake. On the north shore of lake Ontario it will be found that in the vicinity of Whitby there is a division point west of which the resultant shifting movement is westward, and east of it the resultant movement is eastward. The corresponding point on the south shore of the lake lies somewhat to the west of Charlotte. On lake Erie the nodal points are located near Port Stanley on the north shore and Ashtabula on the south. In this lake, at the west end, the presence of point Pelee and the adjacent islands complicates matters somewhat, and we find in the portion of the lake west of the point a slight modification of the general system of movement. The general eastward and westward shifting of the waste at the east and west ends of the lakes is shown both by the transportation of certain well recognized materials, such as fossils from known horizons, and also by the manner in which the waste accumulates around docks land behind them occur marshes and lagoons partly filled by wind-blown

and other obstructions, whether natural or artificial. It is also shown by certain constructive features of the shorelines already described above.

This systematic resultant movement toward the east and west ends of the lakes respectively, from distinct nodal zones, is seen to be directly associated with the size of the storm waves. In the case of lake Ontario, for instance, and the same is true of lake Erie, storms from the southwest will roll waves of the maximum size on the northeast shores of the lake, the wind and waves having free sweep toward this section over the widest part of the lake. Similarly storms from the southeast will roll maximum waves toward the northwest shore of the lake. It is these storm waves with the associated longshore currents which perform the maximum amount of transportation and are the cause of the resultant shifting movements in the directions indicated.

Not only from actual observation may the waves be seen to be greater at the eastern and western ends of the lakes than toward the middle zone at times when storms are blowing toward one or the other end of either lake, but the greater power of these waves is well shown in the height and character of the storm beaches along the shore. Along the middle of the north and south shores of both lakes the storm beaches of coarser debris lie about 6 feet above water level. At the eastern and western ends of the lakes they lie about 15 feet above the same water level, in the case of lake Ontario at least, and probably of lake Erie, being a little higher at the east than at the west.

Again, at or near the middle of the lake shores, below the storm beaches, there is a large accumulation of finer pebbles, gravel, and sand. At the ends of the lakes—this is particularly well shown in New York state at the east end of Ontario—the entire beach is at times made up of very coarse materials, the finer having been rolled out below calm water level.

Summary: Place in Cycle of Shore Development

At the present time, on both lakes, all the minor and many of the major irregularities of the initial shorelines have been corrected, in part by cutting back, in part by the construction of bars and barriers. The present shorelines as a whole are graded, though here and there are sections, partly rock-bound coast, where shore processes have not yet been able to complete the grading. Between the many barriers and the mainsand and delta deposits. Except in the few localities where the shore is rock-bound, the fronts of the sea-cliffs are gently curved, and over large sections they are often nearly straight. Even behind the rock-bound shores the cliffs have gently curved and often graded fronts, but there is usually an ungraded beach between their front and the water's edge, or

possibly no beach at all. Thus, from the general assemblage of shore features found on these lakes, their shores would be classed as adolescent.[6]

COMPARISON OF MODERN ONTARIO AND GLACIAL LAKE IROQUOIS

An extremely interesting comparison can be drawn between the shores of lake Ontario and those of its predecessor, glacial lake Iroquois. The shores of lake Iroquois presented lines of sea-cliffs similar in nearly every respect to those of the present lake; barrier beaches were built across open bays; one of these still retains its lagoon as a small pond, known as Silver lake, near Colborne, Ontario.[7] Flying spits were thrown out from salient points and belts of dunes behind sand beaches were built as on the present lake. An almost exact counterpart of Toronto island is found in an Iroquois flying spit near York, and another in the Davenport gravel ridge north of Toronto. At the west end of lake Iroquois a strong barrier beach was built across the valley between the limestone escarpments, cutting off what is now the Dundas marsh from the main lake, counterparts of the present Burlington beach and bay.

On the south shore similar bars and spits have been noted. One of them, near Pultneyville, New York, was a flying spit similar to that at Scarboro, but pointing eastward.

The type of shore developed on lake Iroquois was very similar to that developed on lake Ontario at the present time, and would be classed as adolescent. Since the disappearance of lake Iroquois, subaerial erosion processes have only slightly modified the abandoned adolescent shorelines. Slips on the sea-cliffs have obscured old beaches; winds and rains have variously modified the old dunes and sand beaches. All the old sea-cliffs are graded to the summit, but in a few cases even yet an occasional slip may occur under special conditions. The original forms of adolescence, while not yet destroyed, are gradually fading and sequential forms of subaerial origin are developing.

In conclusion, the writer wishes to express his obligations to Professor Alfred J. Henry for the tracings from which figures 6 and 7 were prepared and for copies of the two bulletins of the United States Weather Bureau referred to in the text. He is also indebted to Mr James White, Chief Geographer of the Department of the Interior, Ottawa, for tracings from which the figures of Long point, Point aux Pines, and point Pelee were drawn. The balance of the figures are traced either from government maps or were photographed by the author.

[6] Gulliver: Shoreline topography. Proceedings of the American Academy of Arts and Science, vol. xxxiv, 1899.

[7] Coleman: Lake Iroquois, 13th Annual Report, Bureau of Mines, Ontario, 1904.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 19, PP. 501-512 JANUARY 6, 1908

MINE WATERS AND THEIR FIELD ASSAY[1]

BY ALFRED C. LANE

(Read before the Society December 30, 1907)

CONTENTS

INTRODUCTION

No one has done more than he who presides over the Geological Society this year[2] to emphasize the work of water in the deposition of ore and in the metamorphism or change of rocks as they pass down through the two zones of katamorphism, that of leaching or weathering and then that of

[1] Manuscript received by the Secretary of the Society March 5, 1908.
[2] C. R. Van Hise: Theory of metamorphism.

cementation to the deeper zone of anamorphism or upbuilding. His colossal work is, however, largely a systematic application of the principles of modern chemistry and physics to general geological processes, and still leaves room for gleaners to work out detailed applications. Much as the role of underground waters is discussed and masterly as is the handling of the general principles of their action, there are no analyses of such waters given in the Treatise on Metamorphism.

I have been for some time studying the mineral waters and mine waters of Michigan. It is not my wish in this paper to present the results of my studies so much as some methods that may be of service elsewhere and give results which one may use for comparison, different as I believe the origin and history of the copper ore deposits of the southwest are.

Different Sources of Mine Waters

CLASSIFICATION OF WATERS

As is well known, waters have been divided into two classes: (*a*) meteoric or atmospheric waters; (*b*) juvenile or magmatic waters, absorbed in and given off by igneous rocks and derived in part probably from gases originally absorbed in the earth.

As is also well known, Van Hise has laid greater stress on the work of meteoric waters, while Kemp has laid greater stress on the work of igneous intrusions and their attendant emanations in the process of ore deposition. I wish to draw attention to a kind of water which Van Hise includes among meteoric waters, but which is quite different in its role from the downward working rain water. This latter percolates almost pure into the ground from the surface; but, starting as phreatic water practically pure or with but a few parts a million, it dissolves and gradually accumulates mineral content. Even in the first few inches of the soil it becomes much richer in gases, and its capacity to attack feldspars and other rock minerals has been worked up by the chemists of the Department of Agriculture. Its content of carbonates, bicarbonates—perhaps, also, sulphates—soon rises, especially in the arid regions.

Quite different may be the water buried with the beds in the first place, to which we may fitly apply the adjective connate.[3] Most beds are laid down in water which may be either salt or fresh, and may indeed be quite fairly fresh close to the ocean. Such waters have to begin with some—perhaps much—mineral content.

If we retain with Van Hise the term "meteoric" as applicable to all but magmatic waters, we may then divide them into two classes which are of

[3] The Standard Dictionary definition exactly fits the case; the term syngenetic, used in the theory of ore deposits, or congenital, might also be used.

use in studying and discussing the circulation of underground waters. The classification will then be:

I. Meteoric group:
  (*a*) Rain, vadose or *pluvial* waters, coming down from above.
  (*b*) Buried or *connate* waters, which will be very different, according as they were originally *marine* or *fresh*.

II. (Juvenile) or volcanic group:
  (*a*) Magmatic waters. This is in a sense connate in the magma, but not so in the contact zone and country rock.

OCCURRENCE OF CONNATE WATERS

We must of course remember that the property of water is to mix, and that we are sure to meet waters of mixed origin.

If the whole upper zone were so searched and penetrated and rinsed by rain water, as some of Van Hise and Schlichter's diagrams casually inspected have led some to infer, there would be no chance of getting anything but a mixed water or possibly a pluvial or rain water with mineral additions leached in transit. But while Schlichter's lines of flow are presumably correct enough and it is unquestionably true that in any mass of fluid any flow in at one point and out at the other disturbs the remotest corner, yet the amount of flow and rate of change in such remote corner is very small. If it had been possible to show—say by the number of dots per lineal inch—the relative proportions of flow along the lines of flow in these diagrams, it would have given a useful idea of the real main drift of water and the chances of the corners not getting scoured out by rain water. A study of water analyses will show that rain water very frequently does not make a clean job of it. Indeed, one is inclined to agree with the State Geologist of Colorado,[4] who emphasizes a zone of stagnation in which the rain or pluvial waters have had little to do.

When beds are laid down beneath the sea there must be little circulation while they are below water level. If then covered with impervious beds by a transgression of the ocean, there will be no circulation until they are raised so as to outcrop at different levels, when circulation will begin. But in fine-grained rocks capillary action is strong, and even in more pervious ones, if the water is salt, we can hardly expect, nor do we find, indications of very active circulation. On the contrary, where there has been very little orogenic or volcanic disturbance, there are signs of stagnation. Accumulations in domes under impervious cover of oil or gas with salt water beneath must be quite stagnant, and the water at the bottom of many

[4] J. W. Finch: Proceedings of the Colorado Scientific Society, 1904, vol. 7, pp. 193-252, cited by J. F. Kemp.

synclines may be so. We encounter, for instance, around the Lake Superior basin, beginning from 600 feet to 1,600 feet down, a water quite strong in calcium chloride (analysis number 1), which must mark the stoppage of the relatively active circulation of the pluvial or vadose waters of the first thousand feet or so. The chloride water has, to be sure, more sodium chloride in proportion to calcium chloride when first struck than at greater depths, and this may be due to intermingling with upper waters containing carbonates, which have precipitated the calcium as carbonate (analysis number 2). These waters occur, however, not only in the Keweenawan rocks, but in the Huronian, and come in at about the depths given by Finch and Kemp,[5] to wit, 300 to 450 respectively 500 to 600 meters (analysis number 3).

Now it is important to make sure, if possible, whether these waters are (1) downward circulating pluvial waters which have become thus enriched, or (2) originally buried connate waters, or (3) volcanic emanations, such as those recently collected and studied by Lincoln[6] for Kemp.

Table of Analyses.

Analysis number	1.	2.	3.	4.
Location	Quincy mine, fifty-fifth level.	South Kearsarge mine, ninth level.	Republic mine, 1,600-foot level.	Watford, near London, England.
Cl	176,027	702	25,360	12
B_2	2,200	...	...	...
Ca	86,478	91[2]	7,902	110
Na	15,188	414	7,290	11
K_2	411	...	...	—
SO_4	110	75	1,045	7
SiO_2	20	35	...	12
$(FeAl)_2O_3$	10	30	700	...
NH_3	4	...	Mn, Fe trace	NO_3 19
Cu	16	...	n. d.	Org 12
Ni	6	...	n. d.	...
Sr	trace	...	n. d.	...
Ba. Li	0	...	n. d.	...
Mg	20	...	566	—
B	trace	...	n. d.	...
CO_2	0	...	n. d.	156
Sum	280,490	1,347[2]	42,863	338
Total solids	280,500	1,350	45,590	351

[5] J. F. Kemp: Contributions from the Geological Department of Columbia University, vol. viii, no. 61, p. 5. Compte Rendu, International Geological Congress, 10th session, Mexico, 1906, p. 521.

[6] Economic Geology, 1907, p. 258.

(1.) Quincy mine, fifty-fifth level, north drip; analyzed by Dr G. Fernekes. Note how much larger the calcium is relative to the sodium in this than in analyses (2) and (3). See Proc. Lake Superior Mining Institute, 1908, p. 48.

(2.) South Kearsarge mine, ninth level; analyzed by Dr G. Fernekes. Ibid., p. 54.

(3.) Republic mine; analyzed by Dr G. Fernekes. Ibid., p. 10.

(4.) Watford, near London; analyzed by Haywood; cited from Whittaker's table, p. 533.

CEMENTATION A CHECK TO CIRCULATION

It is clear that the downward working pluvial waters can only enter to any considerable extent so far as an outlet for the escape of the buried connate water is opened, and that the process will normally be one of dilution of the connate water, some of which will remain and, homeopathically speaking, be not of a very high potency; but, as Van Hise has well emphasized, the zone of weathering becomes a zone of cementation below, and there is a strong tendency for circulating water, especially on rising and losing heat and pressure, to clog up its own circulation by deposition of the salts it contains. To the extent that exit is thus sealed up we may expect that the buried or connate water will also be hindered in escape.

We are thus led to the theoretic conclusion that a large part of Van Hise's meteoric water is connate; but this purely theoretical conclusion was in fact reached from a study of the chemical character of underground waters.

Chemical Character of Underground Waters

RAIN OR PLUVIAL WATERS

We know the chemical character of rain water and its immediate derivatives fairly well.[7] It falls with a few parts per million of chlorine, derived from the ocean, at the shore. This drops as we leave the seacoast to less than half a part in the Mississippi. There are also traces of nitrates and nitric acid after thunderstorms, and there is a little CO_2; but the total of all constituents other than H_2O is far less than 50 parts per million. Passing through the soil, it is notably enriched in CO_2 and organic acids which change to CO_2, and also, as the Department of Agriculture has shown (Cameron), measurable quantities of the various bases.

When the water gets through this part of its course and becomes the ordinary spring, phreatic, or vadose water, though it varies greatly in character, yet it has generally a certain type. The leading acid ions are

[7] See the Chemische Geologie, by J. Roth; Van den Broeck's "Mémoire sur les Phenomées d'alteration des Eaux Meteoriques"; also Bulletins 28, by Cushman, and 49, by Cameron, of the U. S. Department of Agriculture.

CO_2 and SO_3, and, except in very granitic countries or arid regions, lime and magnesia are the leading bases. The total solids are not commonly over an ounce per cubic foot (1,000 per 1,000,000) and saturation with bicarbonates (= 238 per million $CaCO_3$) seems to be a very common goal. The specific gravity is not markedly greater than that of pure water (is not >1.000).

Analyses of such waters abound. They are the daily work of Leighton's division of the U. S. Geological Survey, and various laboratories testing boiler and sanitary waters. I would emphasize the fact that they do not contain much chlorine relatively. It is a notorious fact that over a few parts per million of chlorine is considered a sign of sewage or other contamination.

Analysis (4) may pass as representative of pluvial and vadose water.[8]

The alkaline waters of arid regions are a group with which I am not very familiar. So far as I have studied analyses of such waters, however, the carbonates and sulphates of sodium and potassium dominate over the chlorides, so that the ratio of sodium to chlorine is high. How high the concentration may be in vadose arid land water I do not know, for it may well be that analysts have avoided them.

CHLORINE CHARACTERISTIC OF SEA WATER

It is not surprising that pluvial and downward working waters do not contain much chlorine, for there are few minerals that contain chlorine: Apatite, relatively rare and insoluble; a little group of volcanic minerals; salt, and our tale is almost told. Unless these salt beds are in the neighborhood, chlorine in the water in considerable quantity seems often to be a sign of connate sea water. Furthermore, this fact is notable: If the water is derived from sodium chloride we may be reasonably sure that there will be at least enough sodium to combine with the chlorine, and in general in superficial and river waters, and those that have derived their mineral content by leaching, there is more than enough sodium for this. But when we find this proportion of chlorine so great that there is more than enough to make sodium chloride, the inference becomes stronger that there is an admixture either of buried sea water or possibly magmatic waters[9] or leachings of a deposit like that of Stassfurt, which is, so far as known, unique.

As analyses which seem to show large proportions of buried sea waters

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[8] See also Roth and the U. S. Geological Survey water supply papers *passim*.

[9] Though the analyses collected by Lincoln, Economic Geology, 1907, p. 298, etcetera, do not indicate any such preponderance of chlorine in such waters.

may be cited Sheboygan, Wisconsin;[10] Saint Louis[11] and East Saint Louis;[12] the Eye Brewery,[13] in England; Norfolk, Virginia;[14] near Bowling Green, Ohio,[15] and many of the waters used as mineral bath waters in Indiana[16] and Michigan.[17]

Some of these are given in the following table:

	Sheboygan.	East Saint Louis.	Bowling Green.
Sodium chloride	306.9436	694.99	2,384.40
Pottassium chloride	14.4822	....	56.24
Lithium chloride	0.1062	....	354.00
Magnesium chloride	54.9139	$MgSO_4$ 130 50	....
Calcium chloride	27.8225	391.80	471.90
Sodium bromide	0.1873	....	....
Calcium sulphate	169.8277	76.05	....
Calcium bicarbonate	13.6585	....	$CaCO_3$ 25.83
Iron bicarbonate	.5044	Fe_2O_3.75	.88
Manganese bicarbonate	.1742	....	....
Calcium phosphate	.0383	....	....
Alumina	.1283	....	.10
Silica	.4665	....	.72
Organic matter	trace	....	....
Iodine	trace	....	....
Barium	trace	....	....
Boron	trace	....	....
Total	589.2536 grains per U. S. gallon.	1,293 60	3,297.93

It seems strongly indicated that the early sea waters contained relatively more calcium chloride than at present. There seems, then, to be some hope of recognizing from the chemical composition of a water—for instance, from the ratio of chlorine to total solids—the proportion of buried sea water. As for connate waters which were fresh—that is, lake or river deposits—the distinction seems much less feasible. Fresh-water lakes often have lime and iron thrown out, and clues may later be discovered, and it may be that in some cases we may from the character of the

[10] Chamberlin's Geology and Geology of Wisconsin, often cited; by C. F. Chandler, 1876, p. 370.
[11] Litton: Saint Louis Academy, and U. S. Geological Survey water supply paper no. 195, p. 161.
[12] Illinois Geological Survey, Bulletin no. 5.
[13] Whittaker, W.: Geology of Suffolk, Cretaceous.
[14] Froehling, 1896, at 1,070 feet, city report.
[15] Orton: Rock waters of Ohio. Nineteenth Annual Report, U. S. Geological Survey, part 4, p. 652.
[16] Blatchley: Twenty-sixth Annual Report.
[17] Lane: U. S. Geological Survey water supply paper no. 31.

water draw inferences as to arid or other conditions of formation of certain beds.

IMPORTANCE OF STUDYING CHEMICAL CHARACTER

From what we have said, the importance of studying the chemical character of waters appears. I have, indeed, speculated on the possibility of the difference in kinds of coal, of oil and gas, of limestone and dolomite being due to variation in the chemical character of the connate water; but, independent of these, we see the importance of water tests, not merely because of the practically different effect upon boilers and mine pumps, but because we may obtain light upon the amount, activity, and direction of underground circulation. If the connate waters are but partially rinsed out, the degree to which they remain and the lines of equal strength must surely mark the channels of underground circulation. For this purpose very many tests must be made. One careful analysis of the mine water as pumped—and that or mere boiler water analyses are what most mine water analyses seem to have been—is obviously of little use. We must begin by making crude quantitative tests from different parts of a mine—in fact, from as many points as a few drops can be collected. We shall then, perhaps, be able to recognize the characteristic types and take of these larger samples, to be more carefully studied.

When the waters are so concentrated as are the deeper mine waters and contain several thousand parts per million of solids, even a sample of 20 or 30 cubic centimeters (a fluid ounce) commonly permits determination of nine-tenths of the constituents with an accuracy something like 1 per cent. This should be enough to trace the main lines of distribution of the different types of water. It is, however, important at times to get an idea of the composition of even a drop or two. In such case examination of a dried drop under the microscope and determination of the index of refraction are available methods.

For such preliminary testing volumetric, nephelometric, and colorimetric methods are obviously the thing, such tests as have been called[18] "The field assay of waters." Tests of this order were made by Davis and myself in Huron county[19] and by Owen in Bay county,[20] and have been reduced to a system and a suit case by M. O. Leighton; but even this suit case is at times too heavy, and a vest-pocket laboratory is needed. Fortu-

[18] M. O. Leighton: U. S. Geological Survey water supply paper no. 151. See also various publications of the U. S. Department of Agriculture, Bureau of Soils, Bulletin no. 31, by O. Schreiner and G. H. Failyer, 1906.

[19] Michigan Geological Survey, vol. vii, part ii.

[20] Michigan Geological Survey, annual report for 1902.

nately the materials for three of the most important tests can be carried literally in a vest pocket.

The rest of this paper consists of hints as to this field testing.

Field Tests of Mine Waters

CONCENTRATION

Determination of total solids.—The first thing is to get an idea of the total solids. In detailed mapping of a mine it may be enough for many samples, and it saves time and chemicals if further tests are to be made to know this. Leighton omits to consider it, because presumably he has surface waters with specific gravity < 1.001 and less than a thousand parts per million of solids in mind; but in mine and the deeper underground waters this test should come first.

Specific gravity.—One index to concentration is the specific gravity. To determine this the physician's urinometer is convenient and cheap (50 to 75 cents). The stem is usually graduated from 1.000 to 1.060 or 1.080, and this is generally enough, and one can get really vest-pocket sizes. They are most nearly accurate for a given temperature 60° to 70° Fahrenheit. If the water is so salt as to have a greater specific weight than 1.060, it may be diluted with three parts of fresh water with specific gravity of 1.000. Very roughly speaking, the excess of the specific gravity above unity in thousandths is eight times the per cent of salts.

Electrical resistance.—Schlichter and the U. S. Department of Agriculture[21] have measured the amount of salts by the electrical resistance.

I have no practical experience with the method. It appears to be much more delicate than the others and practically the only method giving quantitative results with weak concentrations. For how small quantities and how light the apparatus could be made remains to be seen.

Total reflectometer.—The urinometer requires at least an ounce or so of water and is slightly fragile. To test the concentration of a drop or two, the variation in the angle of total reflection seems the most practical method. Bausch and Lomb have made for me, with mutual interchange of suggestions, a pocket total reflectometer, which is figured herewith (figure 1) and gives 70 divisions on the scale between fresh water and salt. It is thus about one-third as sensitive as the urinometer. Of course, the index of refraction is not exactly proportional to the density.

The method of use is as follows: A little of the water to be tested is placed in the triangular prismatic trough A, one side of which is a glass prism, B. Light entering the prism below, through a window at C, is

[21] See the Bureau of Soils field soil book and the methods and references there given.

totally reflected up to an angle dependent on the relative indices of A and B. Thus an objective, D, has part of the field more illuminated than the rest. These parts are separated in daylight by a horizontal colored band. The mine lights are generally more nearly monochromatic. It is perhaps well, by cementing a bit of yellow glass or celluloid, to have the light at C nearly monochromatic. The image of the field is found at E, and there a scale is placed which is viewed by the ocular F. Light should be cut off from entering except by C, by shading by the hand or otherwise. Down in the mine, the sole illumination being from a lamp or candle held a little below C, this causes no difficulty.

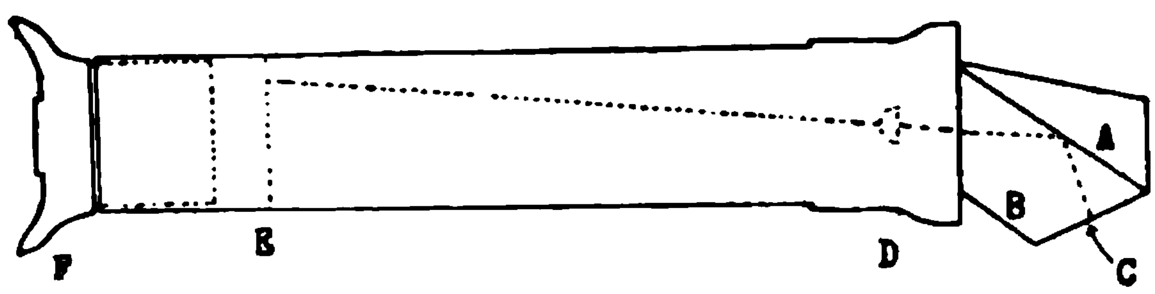

FIGURE 1.—*Outline of Pocket Total Reflectometer*

Outlines of instrument in full line. The course of a ray from C through the glass prism, reflected at the angle of total reflection, reading the scale E, is in dots. The part of the scale above will be more illuminated.

TABLET METHODS

U. S. Geological Survey method.—In following the example of the physicians and having reagents put up with known quantities in tablet form, the U. S. Geological Survey[22] has performed a real service, which enables one to carry in a pocket the chemicals to make three or four important tests. It seems to me this method is capable of much greater development. It must also be remembered that by dissolving a tablet in a known quantity of water a solution of known strength may be obtained, and this is often the most convenient method, if a number of tests are to be made at a time. The accuracy of most of these methods is dependent upon the accuracy with which a quantity of water varying from 20 to 100 cubic centimeters can be measured, and is something like 1 to 5 per cent.

Chlorine.—Leighton's method seems all that could be desired in delicacy, accuracy, simplicity, and convenience. It is fortunate that what in my work appears the most vital determination is so convenient. The potassium dichromate indicator can readily be carried solid. Less than a cubic millimeter need be dissolved.

In the case of waters likely to be strong, it will be well to add the potassium dichromate and a tablet or more of silver nitrate to distilled water, or a water whose chlorine has been determined, then from a burette drop

[22] Leighton: Water supply paper no. 151, p. 51.

in enough of the strong water to discharge the red color. Then, having found the amount of chlorine in it, a known greater quantity of the water may be added and enough tablets then to bring back the red color. One may thus alternate two or three times.

Carbonates.—Leighton's test, the addition of sodium acid sulphate with methyl orange or phenol phthalen, as indicators, is as simple as the chlorine test, but not so trustworthy, since it will not work in the presence of calcium chloride, for instance. This gives the acid reaction at once, even though carbonates are really present.

A solution of soap and soda, pink with phenol-phthalein, is made colorless by enough of the strong calcium chloride waters, and may be as a rough index of the amount of calcium chloride.

Hardness.—The test for hardness (Ca and Mg) with soap tablets, equivalent to a known amount of $CaCO_3$, is also a practical vest-pocket test. In strong mine waters it has been found well to make up a solution of a number of tablets in a known amount of water, and then add the water from a graduated burette until the foam is discharged.

In general.—Material for the above tests can be carried in the vest pocket and are those I have most used, especially the chlorine.

TURBIDITY METHODS

Chlorine.—Other tests have been devised which involved forming a precipitate and seeing how opaque or turbid it made the water. For instance, in our Huron County work,[23] Davis and I graded them as --trace, precipitate with $AgNO_3$ opalescent, less than 100 per million Cl present; low, precipitate with $AgNO_3$ milky, 200 to 600 per million Cl present; medium, precipitate with $AgNO_3$ curdled, 600 to 1,300 per million Cl present, with a taste; above this the salty taste was distinct.

In Leighton's tests a portable electric light and battery are used, which are rather heavy. No doubt other methods more portable, but perhaps less accurate, could be devised which would suffice to compare the various waters found in a particular mine. It might be well to have made up tablets containing known amounts of substances to be tested for, which could be used to make solutions for comparison.

Calcium.—Leighton did use the turbidity produced by ammonium oxalate with a little excess of ammonia, but it has been canceled. It seems to work pretty well with our waters.

Sodium carbonate might be used, allowing for the small amount (30 parts per million or so) of calcium carbonate that would remain.

[23] Volume vii, Michigan Geological Survey, part ii, pp. 139-141.

Magnesium.—Mr Charles Catlett[24] has described a field test for magnesia dependent on the fact that lime is much more soluble in sugar than magnesia, which ought to be made available. Good field tests for magnesium and sodium are still lacking.

Sulphates.—The turbidity tests for sulphates is on the precipitate made in an acid barium chloride solution, and the method devised by Jackson and used by Leighton has been recently reexamined by Parr.[25]

Sulphur.—The browning by acetate of lead has been used, but is hardly quantitative.

COLORIMETRIC TESTS

Instead of standard comparative solutions, tinted glasses may be used.

Leighton's test for iron with KCNS involves carrying nitric acid around, which is awkward.

The ink test with tannin—that is, cold tea—is quite as delicate, but the resultant tint varies, being violet in carbonated waters, cider-colored if ammonia is added, and discharged by acids. It may be used comparatively in one suite of waters. Perhaps it would be better to always make the solution alkaline.

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[24] Bi-monthly bulletin of the American Institute of Mining Engineers, September, 1907.
[25] Bulletin no. 3, Illinois Geological Survey.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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PROCEEDINGS OF THE TWENTIETH ANNUAL MEETING, HELD AT ALBUQUERQUE, NEW MEXICO, DECEMBER 30 AND 31, INCLUDING PROCEEDINGS OF THE NINTH ANNUAL MEETING OF THE CORDILLERAN SECTION, HELD AT THE SAME PLACE AND TIME.

EDMUND OTIS HOVEY, *Secretary.*

CONTENTS

Session of Monday, December 30

The Society was called to order by President Charles R. Van Hise at 9.15 o'clock a m, at the University of New Mexico. A cordial address of welcome was delivered by President W. G. Tight, of the University of New Mexico, to which response was made by President Van Hise.

The report of the Council was called for, and was presented by the Secretary, in print, as follows:

REPORT OF THE COUNCIL

To the Geological Society of America,
in Twentieth Annual Meeting assembled:

The regular annual meeting of the Council was held at New York in connection with the meeting of the Society. There have been no special meetings during the year.

The details of administration for the nineteenth year of the existence of the Society are given in the following reports of the officers:

Secretary's Report

To the Council of the Geological Society of America:

Meetings.—The proceedings of the annual meeting of the Society held at New York city December 27, 28, and 29, 1906, have been recorded in the closing brochure of volume 18 of the Bulletin, which is now in press.

Membership.—During the past year the Society has lost two Fellows by death: James M. Safford and Angelo Heilprin. The resignation of one Fellow has been accepted. The names of the fourteen Fellows elected at the New York meeting have been added to the list, all of them having completed their membership according to rule. The present enrollment of the Society is 294, or 11 more than at the time of making the last annual report. Four candidates are before the Society for election and several applications are under consideration by Council.

Distribution of Bulletin.—There have now been distributed 17 brochures comprising 448 pages of volume 18, and the remaining four brochures, including the Proceedings, are in the hands of the printers in various stages of completion. By action of the Publication Committee no manuscripts were accepted by the Secretary after November 1, in an

effort to finish the volume within the calendar year. Partly through the slowness of authors in sending back proofs, the result has not been accomplished. Hereafter the rule which provides that "printing shall not be delayed by reason of absence or incapacity of authors more than one week beyond the time ordinarily required for the transmission of mails" (*vide* Bull., vol. 5, p. 649) should be enforced. Authors are urged also to send in their manuscripts earlier. The irregular distribution of the Bulletin during the past year has been as follows: Complete volumes, including one complete set, sold to Fellows, 28; sold to the public, 103; sent out to supply deficiencies, 2; brochures sent out to supply deficiencies, 57; sold to Fellows, 47; sold to the public, 37. A complete set of paleontologic and stratigraphic papers has been given to the Concilium Bibliographicum of Zürich. Three copies of volume 17 have been bound for the use of officers and the library, and one complete set has been bound for the Secretary's office. This set remains the property of the Society.

Bulletin Sales.—The receipts from the sale of the Bulletin during the past year are shown in the following table:

Bulletin Sales, December 1, 1906, to November 30, 1907

	Complete volumes.			Brochures.			Grand total.
	Fellows.	Public.	Total.	Fellows.	Public.	Total.	
Volume 1	$9.00	....	$9.00	$1.15	$0.40	$1.55	$10.55
Volume 2	9.00	....	9.00	....	1.00	1.00	10.00
Volume 3	8 00	....	8.00	....	.12	.12	8.12
Volume 4	7.00	....	7.00	.20	.30	.50	7.50
Volume 5	8.00	....	8.00	.25	.57	.82	8.82
Volume 6	8.00	....	8.00	.10	....	.10	8.10
Volume 7	8.00	....	8.00	....	.60	.60	8.60
Volume 8	8.00	....	8.00	....	.30	.30	8.30
Volume 9	8.00	....	8.00	1.25	.30	1.55	9 55
Volume 10	8.00	....	8.00	.55	.80	1.35	9.35
Volume 11	9.00	....	9.00	.55	2.20	2.75	11.75
Volume 12	4.00	....	4.00	.25	3.85	4.10	8.10
Volume 13	4.50	$5.00	9.50	....	1.44	1.44	10.94
Volume 14	4.50	....	4.50	....	4.60	4.60	9.10
Volume 15	4.50	5.00	9.50	1.55	2.40	3.95	13.45
Volume 16	4.50	25 00	29.50	1.70	1.35	3.05	32.55
Volume 17	4.50	145.00	149.50	.70	4.55	5.25	154.75
Volume 18	....	305.00	305.00	....	.25	.25	305.25
Volume 19	....	30 00	30.00	....	....	....	30.00
Total	$116.50	$515.00	$631.50	$8.25	$25.03	$33.28	$664.78
Index	2.25	4 75	7.00	....	....	....	7.00
	$118.75	$519 75	$638.50	$8.25	$25.03	$33.28	$671.78

Receipts for the fiscal year	**$671.78**
Previously reported	**9,602.34**
Total receipts to date	**$10,274.12**
Charged, but not yet received:	
On 1906 account	**80.00**
On 1907 account	**35.40**
Total sales to date	**$10,389.52**

The bills for volume 18 have not been sent out to volume subscribers yet, and the table given above includes only actual payments.

The cost of publishing the Bulletin, volumes 1-17, has been $33,414.91, the average cost per volume being $1,965.58. These figures, however, do not include the expense of distribution. The number of pages and illustrations in the volumes has increased so much during the past few years that the price of subscription for libraries and foreign individuals should be raised. The present price does not cover the actual cost of publication, and is about one-third less than the price charged by other societies for volumes corresponding with our Bulletin in number and size of pages and plates and in quality of paper and printing.

Expenses.—The following table gives the cost of administration and of Bulletin distribution during the past year. The expense of moving the Secretary's office from Rochester to New York has made the outgo for "Administration" unusually high.

EXPENDITURE OF SECRETARY'S OFFICE DURING THE FISCAL YEAR ENDING NOVEMBER 30, 1907

Account of Administration

Postage and telegrams	$37.73	
Expressage and freight	14.73	
Printing (including stationery)	240.38	
Addressograph links	1.34	
Binding 3 copies volume 17	3.00	
Office furniture and storage closet	136.63	
Meetings (expenses of Cordilleran Section)	16.31	
Total		$450.12

Account of Bulletin

Postage	$138.63	
Expressage and freight	80.40	
Paper and printing	11.15	
Addressograph links	.50	
Laborers	5.50	
Storage closet	51.45	
Binding set of Bulletin	28.60	
Collection of checks	4.75	
Total		$320.98
Total expenses for the year		$771.10

As soon as possible after the New York meeting the transfer to the custody of the present incumbent of the material pertaining to the Secretary's office was finished. The Society is to be congratulated upon the care and completeness with which all its records from the beginning have been preserved, and I wish here to express my personal appreciation of the help rendered me by Professor Fairchild in starting upon the somewhat arduous though very pleasant duties of the secretaryship.

Respectfully submitted.

EDMUND OTIS HOVEY,
Secretary.

NEW YORK, *December 18, 1907.*

TREASURER'S REPORT

To the Council of the Geological Society of America:

The Treasurer herewith submits his annual report for the year ending December 1, 1907:

Three (3) Fellows, J. A. Dresser, Ida H. Ogilvie, and George I. Adams, have commuted for life during the year by the payment of one hundred dollars each, thus increasing the total Life Commutations to seventy-nine (79) at the present time.

Two (2) Fellows are delinquent for four years and three (3) Fellows for three years, and are therefore liable to be dropped from the roll for the non-payment of dues, in accordance with section 3, chapter 1, of the By-laws; eleven (11) Fellows are delinquent for two years; while thirty-one (31) Fellows, on the date of the preparation of this report, are delinquent for the present year.

The membership of the Society, including delinquents, aggregates at the present time 294, of whom 79 have commuted for life. There have been 2 deaths and 1 resignation during the past year.

The Treasurer received from his predecessor on December 1, 1906, the following securities:

	Par value
Two (2) Texas and Pacific Railroad first mortgage five per cent bonds, cost $1,976.25	$2,000.00
Three (3) U. S. Steel Corporation second mortgage five per cent bonds, cost $2,366.25	3,000.00
Ten (10) shares of the capital stock of the Iowa Apartment House Company, Washington, D. C., cost $1,000.00	1,000.00
Forty (40) shares of the capital stock of the Ontario Apartment House Company, Washington, D. C., cost $4,000.00	4,000.00
Total cost, $9,342.50; total par value	**$10,000.00**

These securities have been placed in a safe-deposit box in the Baltimore Trust and Guarantee Company, Baltimore, Maryland, where the funds

of the Society are also deposited, and where the unexpended monthly balance draws three per cent interest.

The general financial condition of the Society is exhibited by the following tabular statement showing the receipts and disbursements for the year ending December 1, 1907:

RECEIPTS

Balance in treasury December 1, 1906		$1,997.41	
Fellowship fees 1905 (3)	$30.00		
" " 1906 (21)	210.00		
" " 1907 (168)	1,680.00		
		1,920.00	
Initiation fees (14)		140.00	
Life commutations (3)		300.00	
Interest on investments:			
Iowa Apartment House company	$60.00		
Texas and Pacific railroad bonds	100.00		
Ontario Apartment House company	220.00		
U. S. Steel Corporation bonds	150.00		
Interest on deposits to January 30, 1907, Rochester Security Trust Company	11.45		
Interest on deposits to June 30, 1907, Baltimore Trust Company	27.94		
		569.39	
Sales of publications		671.78	
			$5,598.58

EXPENDITURES

Secretary's office:			
Administration	$493.57		
Bulletin	277.53		
Allowance	500.00		
		1,271.10	
Treasurer's office:			
Postage, express, etc.	$39.05		
Clerical hire	50.00		
		89.05	
Librarian's office		8.42	
Publication of Bulletin:			
Printing	$2,042.63		
Engraving	492.73		
Editor's allowance	250.00		
		2,785.36	
Miscellaneous		10.50	
		$4,164.43	
Balance on hand December 1, 1907		1,434.15	
			$5,598.58

Respectfully submitted.

WM. BULLOCK CLARK,
Treasurer.

DECEMBER 6, 1907.

EDITOR'S REPORT

To the Council of the Geological Society of America:

Before submitting the usual statement as to the progress made in the publication of the annual volume, the Editor desires to call the attention of the Council to the desirability of appointing a committee to formulate, as nearly as may be practicable, the future usage of the Society in regard to capitalization, abbreviations, and similar matters. The committee should have authority to ascertain so far as possible the wishes of each member, in order to determine the preference of the majority. This may seem a trivial matter, but it is the cause of some irritation, which should be removed by some such method as that suggested. It is certainly but fair that the members should be given a chance to express their individual views. The report of the committee would practically fix the standards in a fashion satisfactory to the members generally, relieve the present Editor and his successors from some embarrassment, and be of value in many other ways. The report should include brief suggestions as to the form in which papers should be presented, in order to lighten the Editor's labors as much as possible. It has been the experience of the present Editor that the authors of papers do not intentionally add to the Editor's burdens. It is because they have had, unless connected with institutions like the Geological Survey, no experience as to the form in which manuscripts should be prepared. If suggestions such as those indicated were included in the report, and accompanied by appropriate illustrations, it is believed they would be appreciated by members.

By reason of the decision of the Publication Committee that papers not in hand prior to November 1 should be excluded, all of volume 18 is now in type, except the proceedings of the Cordilleran Section, the manuscript of which has not been received at this date. This year's experience indicates that if it is desired that the annual volume should be issued previous to the winter meeting, the time limit of submission of papers must be still further shortened.

	Average. Vols. 1-12.	Vol. 13.	Vol. 14.	Vol. 15.	Vol. 16.	Vol. 17.	Vol. 18.
	pp. 577. pls. 43.	pp. 583. pls. 58.	pp. 609. pls. 65.	pp. 636. pls. 59.	pp. 636. pls. 94.	pp. 785. pls. 84.	pp. 717. pls. 74.
Letter-press	$1,575 14	$1,647 12	$1,657 50	$1,661 21	$1,817 03	$2,087 98	$2,015 68
Illustrations	327 62	477 27	431 21	457 76	706 97	608 68	486 22
	$1,902 66	$2,124 39	$2,088 71	$2,118 97	$2,524 00	$2,696 66	$2,501 90
Average per page	$3 30	$3 64	$3 43	$3 33	$3 96	$3 37	$3 42

Classification.

Volume.	Areal geology.	Physical geology.	Glacial geology.	Physiographic geology.	Petrographic geology.	Stratigraphic geology.	Paleontologic geology.	Economic geology.	Official matter.	Memorials.	Unclassified.	Total.
	Number of pages.											
1.......	116	137	92	18	83	44	47	.....	60	4	4	593+xii
2.......	56	110	60	111	52	168	47	9	55	1	7	662+xiv
3.......	56	41	44	41	32	158	104	.....	61	15	1	541+xii
4.......	25	134	38	74	52	52	14	.....	47	32	2	458+xii
5.......	138	135	70	54	28	51	107	.....	71	14	9	665+xii
6.......	50	111	75	39	71	99	1	.....	63	25	4	538+x
7.......	38	77	105	53	40	21	123	4	66	28	13	558+x
8.......	34	50	98	5	43	67	58	14	79	8	....	446+x
9.......	2	102	138	.....	44	28	64	16	64	12	....	460+x
10.......	35	33	96	37	59	62	68	28	84	27	17	534+xii
11.......	65	110	21	10	54	31	188	7	71	60	46	651+xii
12.......	199	39	55	53	24	98	5	5	70	2	....	538+xii
13.......	125	17	13	24	28	116	42	4	165	32	29	583+xii
14.......	48	47	48	59	183	118	22	1	80	14	1	609+xii
15	26	124	3	94	36	267	.....	.....	77	17	3	636+x
16.......	64	111	78	30	102	141	19	.....	67	22	15	636+xii
17.......	49	161	41	84	47	294	27	.....	71	9	2	785+xiv
18.......	16	164	141	5	29	246	5	.....	68	40	3	717+xii

It is not practicable, for the reasons indicated above, to give the exact number of pages, but there will probably be about 700. The volume will be illustrated with 67 half-tone plates and 62 text figures.

Respectfully submitted.

JOSEPH STANLEY-BROWN,
Editor.

COLD SPRING HARBOR, N. Y., *December 16, 1907.*

LIBRARIAN'S REPORT

To the Council of the Geological Society of America:

The accessions to the Library during the past year have been listed and acknowledged, and the list of these accessions for the year ending October 1 has been forwarded to the Secretary for incorporation in volume 18 of the Bulletin. The binding of complete volumes of exchanges is steadily cared for by the Case Library.

The most notable addition to the library during the year past has been the nearly complete set of the Verhandlungen des Verein der Preussischen Rheinlände, some 60 volumes, sent in exchange for a complete set of our Bulletin.

The expenses of this office for the past year are as follows:

To clerk hire	$6.00
To express	1.00
To postage	1.42
	$8.42

Respectfully submitted.

H. P. CUSHING,
Librarian.

CLEVELAND, OHIO, *December 2, 1907.*

On motion of the Secretary, it was voted to defer the consideration of the Council report to the following day.

As the Auditing Committee to examine and report upon the accounts of the Treasurer, the Society elected G. K. Gilbert, C. W. Hayes, and A. H. Purdue.

ELECTION OF OFFICERS

President Van Hise then announced the result of balloting for officers for 1908, as canvassed by the Council, and declared the following officers elected:

President:

SAMUEL CALVIN, Iowa City, Iowa.

First Vice-President:

GEORGE F. BECKER, Washington, D. C.

Second Vice-President:

A. C. LAWSON, Berkeley, California.

Secretary:

EDMUND OTIS HOVEY, New York city.

Treasurer:

WILLIAM BULLOCK CLARK, Baltimore, Md.

Editor:

JOSEPH STANLEY-BROWN, Cold Spring Harbor, N. Y.

Librarian:

H. P. CUSHING, Cleveland, Ohio.

Councilors:

H. P. CUSHING, Cleveland, Ohio.
H. B. PATTON, Golden, Colorado.

ELECTION OF FELLOWS

The Secretary stated that the candidates for fellowship had been elected by the transmitted ballots, with but few dissenting votes. The list is as follows:

CLARENCE EDWARD DUTTON, A. B. (Yale, '60), Major, U. S. A. (retired), Englewood, New Jersey.

D. P. PENHALLOW, B. S., M. S., Sc. D., Botanical Laboratories, McGill University, Montreal, Canada. Professor of Botany, McGill University.

PERCY EDWARD RAYMOND, B. A., Ph. D., Pittsburgh, Pennsylvania. Assistant Curator of Invertebrate Fossils, Carnegie Museum.

THOMAS EDMUND SAVAGE, A. B., B. S., M. S., University of Illinois, Urbana, Illinois.

NECROLOGY

On call of the President, memorials of the Fellows who had died since the New York meeting were read as follows:

MEMOIR OF JAMES MERRILL SAFFORD

BY J. J. STEVENSON

James Merrill Safford, Ph. D., M. D., was born in Zanesville, Ohio, August 13, 1822, and died in Dallas, Texas, July 3, 1907. He was descended from sturdy New England ancestry, Thomas Safford having come from England to Massachusetts in 1630. The family was important in colonial times, and in later days counted among its members many prominent physicians. His father moved to Zanesville shortly before the birth of Professor Safford. He received his preparatory training in Zanesville and afterwards attended the Ohio University at Athens, where he was graduated in 1844. He spent two years in study at Yale, and soon after his return he was called to Cumberland University, at Lebanon, Tennessee, as professor of chemistry and natural history, where he remained until 1873, when he was chosen professor of chemistry in the medical school of the University of Nashville. Vanderbilt University was opened in 1875, and the chair of geology and natural history was assigned to him; he remained in full discharge of the duties until 1900. During much of this time he delivered the chemical lectures in the medical department, and for several years he was dean of the college of pharmacy. He was member of the State Board of Health from 1866 to 1896, and during the greater part of that period was vice-president of the board.

Professor Safford's geological work began in 1850, and his first recorded paper was published in 1851, when most of the Fellows of this

Jas. M. Safford

Society were not yet born. He received appointment as State Geologist of Tennessee in 1854. His first report, 164 pages, with preliminary map, was published in 1856, and was mainly a reconnaissance study of the mineral resources, but the final chapter gives a geological sketch exhibiting the formations recognized in the state. A "Biennial Report," published in 1857, was merely a brief statement of results. In 1860 the legislature ordered the preparation and publication of a final report, but the civil war followed quickly, and for a time survey work was at an end. In 1868 the state found itself in condition to reauthorize the publication. The report was completed, and it was published in 1869 as the "Geology of Tennessee," 550 pages, with map and 7 plates.

It is difficult for geologists of our day to do full justice to a work like this "Geology of Tennessee," the outcome of field studies made fifty years ago. There were no maps, for much of the state was still wilderness; mines were few; the roads were on natural grades; there was no network of railroads to give sections in critical places. Professor Safford had no instruments except a compass and a pocket level, and the appropriation was so small that he was without means to procure those aids without which a modern geologist would think himself almost helpless. Over much of the area he could not ride, and a great part of the 11,000 miles traveled during prosecution of the work was done on foot; he was compelled to live off the country and to endure the more than inconveniences inseparable from lodging in the uncomfortable houses of mountaineers. Yet in this modest volume he gave a conspectus of Tennessee geology which has borne the most exacting review. It is the outcome of twenty years of labor, carried on mostly at his own expense.

In this volume the succession of the earlier Paleozoic formations is presented in detail and numerous subdivisions are suggested, most of which have been accepted by geologists, and they bear the names given by him. Later studies in more northerly areas have led to some modifications of his grouping, but these are based on careful investigation of fossils such as was unknown in his day. The Black shale underlying the Carboniferous was recognized as Devonian, and he noted the absence of some formations which are prominent farther north in the Appalachian basin. The description of the Carboniferous is brief, counted in pages, but the sections are in such detail and are discussed so clearly that the relations of the beds are set forth sharply in all except the extreme northeast portion of the Cumberland plateau, to which he had been able to devote little attention; yet even there he had succeeded in securing a type section. He differentiated the Tertiary and Quaternary subdivisions and described and figured fourteen new species of fossils. An ad-

mirable summary of the state's economic resources closes the volume. For compactness and clearness, this work is not excelled, perhaps not equaled, by any other official report published in this country.

The office of State Geologist was restored in 1871, and Professor Safford received the appointment to the position, as well as to that of Chemist to the Board of Agriculture. No reports as State Geologist are credited to him, though he held the post until 1899; but he was coeditor of the "Introduction to the Resources of Tennessee," a stout volume of 1193 pages, published in 1874. This contains a geological sketch of each county, adding much important material to that contained in his earlier volume. He was coeditor also of a text-book on the geology of his state, intended for use in the schools, and he published many brief articles bearing on geological questions of local interest. In 1884 he contributed to the census reports a careful discussion of the physico-geography and agricultural features of Kentucky and Tennessee, and in 1888 he published a new edition of his map of the state. In 1891 he published a discussion of the geology of the state in relation to water supply, and in the same year he contributed two papers to the Bulletin of this Society.

It was a misfortune for Professor Safford and his fellow-geologists that during most of his life he was, so to say, isolated. He attended meetings of the Association and of this Society when they were within his reach, and he always contributed much of value to the discussions; but he was known in the flesh to comparatively few of his fellow-workers, so that he labored under the disadvantage of being known only by his writings, most of which belong to a period of which some are apt to think, if not to speak, disrespectfully. He was a man among men, everywhere commanding respect by his common sense, his integrity, and his manly recognition of others. The excellence and importance of his geological work became fully known to most of us only during the last decade, but throughout his life his worth was recognized by Tennessee, in which for more than forty years he was one of the foremost citizens.

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1853. Note on tooth of *Petalodus ohioensis*. *American Journal of Science*, second series, vol. 16, p. 142.

On the parallelism of the Lower Silurian groups of middle Tennessee with those of New York. *Proceedings of the American Association for the Advancement of Science*, vol. 7, pp. 153-156. *Annals of Science*, vol. 1, pp. 249-251.

1856. Remarks on the genus Tetradium, with notices on the species found in middle Tennessee. *American Journal of Science*, second series, vol. xxii, pp. 236-238.

A geological reconnaissance of the state of Tennessee; the author's first biennial report; 164 pages, with map. Nashville, 1856.

1857. Second biennial report [on the geology of Tennessee]. 11 pages, 8°. Nashville, 1857.

1858. On Tennessee geological history. *American Journal of Science*, second series, vol. 26, pp. 128-129.

1859. [Third biennial] Report of the state geologist. 8 pages, 8°. [Nashville, 1859.]

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1861. The Upper Silurian beds of western Tennessee, and Dr F. Roemer's monograph. *American Journal of Science*, second series, vol. xxxi, pp. 205-209.

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Note on the geological position of petroleum reservoirs in southern Kentucky and in Tennessee. *American Journal of Science*, second series, vol. xlii, pp. 104-107.

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1869. Geology of Tennessee, vol. xii, 550 pages, 8 plates, map, 8°. Nashville, 1869.

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1885. Geological and topographical features of Tennessee in relation to disease. First Report of the Tennessee State Board of Health, pp. 237-315. Nashville, 1880. Second Report, pp. 365-385. Nashville, 1885.

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MEMOIR OF ANGELO HEILPRIN

BY HERBERT E. GREGORY

With the death of Angelo Heilprin this Society has lost one of its prominent members, Yale University one of its ablest instructors, and geography its best known leader in America. While his work was largely geographic, his contributions to geology were many and important.

A glance at the life of Heilprin reveals an interesting career, in which inherited aptitude, increased by constancy of effort, ripened into power of an unusual sort. His grandfather, Phineas Mendel Heilprin (1801-1863), was a prominent student of Hebrew and philosophy, and his father, Michael Heilprin (1823-1888), likewise was a scholar of wide repute. Owing to persecution in Poland, Angelo Heilprin's parents

escaped in 1842 and settled in Hungary, where Angelo was born, March 31, 1853. During the war for Hungarian freedom (1848-1849) the elder Heilprin was an associate of Kossuth, and, as a result of his activities in the revolution, was forced to flee, coming to America in 1856, where he later pursued a literary career.

Angelo Heilprin's early education was in the public schools of Brooklyn, but the most valuable instruction was undoubtedly that received in the home, where, with his father and brother Louis, he was constantly in an atmosphere of refinement and intellectual power. His taste for exploration and scientific study developed early. Throughout his boyhood he cared little for the ordinary light literature, but confined his reading pretty largely to stories of travel, and while yet a boy undertook tramps of considerable length in search of adventure. He early began to draw in color, and it is related that at the age of six he made a map of Greenland which was of unusual accuracy, and when this was shown to him later in life he expressed his doubt that it could be the work of a schoolboy. In the home circle he was constantly encouraged to read and to express himself in writing, as a result of which he was able when only in his twentieth year to be of much help in the preparation of articles for the American Cyclopædia, his sketch of John Tyndall in particular being a very creditable piece of work. In 1876, at the age of twenty-four, he decided to study with the famous masters of the day, and enrolled himself as a pupil in the Royal School of Mines, under the tutelage of Huxley in biology, Etheridge in paleontology, and Judd in geology. Later he studied in Paris, and in Geneva with Carl Vogt. Other European centers of culture were visited, and in each place Heilprin made the most of his opportunities, adding to his store of knowledge and developing his methods of research and instruction.

After three years of European study, Heilprin returned to America and began his connection with the Philadelphia Academy of Natural Sciences, being elected professor of invertebrate paleontology in 1880, curator in charge in 1883, and professor of geology in 1895, holding the last position till 1899. He was also associated with the Wagner Free Institute of Science, of which he became the curator. His connection with these organizations, together with writing and lecturing, constituted the chief routine of his life until 1904, when he came to Yale University as lecturer in physical geography, a position which he occupied at the time of his death.

The geographic activity of Heilprin includes exploration, investigation, and educational work. As an explorer he turned his attention to widely separated parts of the world. His first important expedition, in

1886, was to the Everglades of Florida, as the result of which he showed that the larger part of the peninsula was of Tertiary age and had not been built by recent coral activity; the existence of marine Pliocene deposits in the United States was also made known for the first time. As stated by Doctor Leidy, "The well observed facts of the report must greatly modify the opinions which have generally been held in regard to the geological construction of the peninsula of Florida."

In 1889-1890 he made his first expedition to Mexico, where a study was made of Yucatan and of the Mexican plateau, particularly with reference to the volcanoes and enormous deposits of lavas. In that year he climbed Orizaba, Popocatepetl, Nevada de Toluca, and Ixtaccihuatl, determining their heights and showing Orizaba to be the loftiest mountain at that time known in North America.

The Peary Relief Expedition of 1892 was one of the most important undertakings of Heilprin. The success of this expedition could only have been brought about by skill and bravery of the highest type, both of which qualities the leader of the expedition possessed. His book descriptive of this expedition, namely, "The Arctic Problem," is one of the most fascinating narratives in geographic literature. It is so modestly written that the reader hardly grasps the importance of the work and fails to realize that the meeting of Heilprin and Peary on the ice-cap was one of the most dramatic scenes in the history of exploration. Peary has expressed his appreciation in the following words: "My own obligations to and regard for him are particularly great. To him more than to any one else is due the activity of this country in arctic and antarctic work during the past fifteen years."

In 1896 Heilprin made an expedition into Morocco, Algeria, and Tunis. With great skill he made his way among the semi-civilized tribes in pursuit of data which led to the conclusion that the mountains of Morocco and Algeria had not been glaciated during Pleistocene times.

The year 1898 was spent on an excursion to Alaska, an account of which is given in his volume, "Alaska and the Klondike," which is full of interesting material, much of it of economic value.

In 1902, when the news of the destruction of Saint Pierre was received, Heilprin, with characteristic activity and decision, took the first steamer for Martinique, and on March 20 of that year ascended Pelée while it was still in a violent state of eruption. On this day and the days following he was in constant danger, and really took his life in his hands for the sake of studying at first hand the process of volcanic eruption. One is reminded of those earlier scientists, Empedocles at Etna, 430 B. C., and Pliny at Vesuvius, 79 A. D., both of whom paid for their

scientific zeal with their lives. Fortunately Heilprin was spared, and lived to write his valuable papers dealing with the phenomena of this extraordinary expression of vulcanism.

Heilprin's excursion to British Guiana, in 1906, was designed as the first of a series of expeditions which were to be made into tropical regions. This expedition was, however, destined to be his last, for the fever contracted at this time was never fully checked, and was one of the chief causes which led to his death, on July 17, 1907.

As an educator, Professor Heilprin's influence was widespread. He was one of the first to recognize the value of photographic reproduction in the teaching of the earth sciences, and in this respect his "Principles of Geology" has set the pattern for later successful works. The great skill with which he was able to present important geological principles by the use of the most common objects is well shown in his "Town geology: the lesson of the Philadelphia rocks." Heilprin may well be called the natural teacher. His manner of presentation was very effective, and whether with the class in the field or conducting recitations, giving lectures before teachers, or public addresses, the expounder of science as well as the explorer and investigator was evident. In the experience of the writer, no teacher of geography has been more effective with classes than has Heilprin. Students readily recognized him as a master—learned and cultured, and at the same time modest, sympathetic, and democratic. As a teacher at Yale he never attempted to control his classes or to secure good work by any of the devices of pedagogues, but trusted to the value of the subject and to his method of presentation to arouse interest in the student.

Heilprin was a firm adherent to the doctrine that a knowledge of the earth and its inhabitants is an essential part of a general education having high cultural value. To him, therefore, a wide dissemination of the results of geographical study was of the first importance, and small groups of geographers devoting their attention to highly technical matters were of relatively minor importance. When the Association of American Geographers was formed—an association designed to separate the professional geographers from those merely interested in geography—Heilprin's objection was characteristic; he thought that such an association might tend to limit the distribution of geographical information.

Likewise a museum to him was a place for teaching the truths of nature, not a place for storing and protecting specimens, and his successful effort to open the museum in Philadelphia on Sundays has been imitated with advantage by other institutions.

His influence as an educator was also exerted through societies and

periodicals. It is largely due to his influence that the Geographical Society of Philadelphia has become such a prominent educational factor. He was one of the founders of the Alpine Club of America. In 1893 he established the magazine "Around the World," the forerunner of the National Geographic Magazine, of which latter periodical he was one of the editors. At the time of his death he was an active member of a number of organizations and was president of the Association of American Geographers.

Professor Heilprin's versatility was one of his most marked characteristics. A scientist of the first rank, still he was widely read in literature and history. He was master of arts, too—not ordinarily associated with scientific men. Those who have had the pleasure of listening to Heilprin at the piano, as he was interpreting Hungarian folk songs, dances, or patriotic hymns, will agree that his musical ability was extraordinary. He began early to show traits of an artist. When but eleven years of age he obtained permission to copy the paintings in the capitol at Washington, and while still a young man his paintings were on exhibition in the principal cities of eastern United States. His last painting of the Pelée tower ranks among the best productions of landscape artists. They show technique which is of high order and a mastery of drawing and of color. As has been said by a well known critic, his art is "the art of a painter, not the art of a scientist." He also possessed mechanical genius, which led to the invention of several devices for which patents were secured.

As a man, Heilprin was characterized by energy, concentration, and continuous application—qualities which bring success. His modest and quiet bearing was marked, and in his associations with his fellow-men he never assumed an egotistical attitude. He preferred to be considered one of an army of fellow-workers presenting the beauties of nature to the human mind. He had a genuine zeal for scientific truths, and a foresight which led him to devote his energies to important lines of work. The writer recalls with pleasure little talks with his friend on geography, education, university ideals, and kindred topics, all of which were inspiring and in all of which Heilprin revealed himself as a modest, open-minded, yet energetic searcher after truth.

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After the reading of the memorials of the deceased Fellows the regular program of papers was taken up as follows:

OCCURRENCE OF PROUSTITE AND ARGENTITE AT THE CALIFORNIA MINE NEAR MONTEZUMA, COLORADO

BY FRANK R. VAN HORN

This paper has been published as pages 93-98 of this volume. Discussion by C. R. Van Hise, George D. Louderback, and H. E. Gregory.

MINE WATERS AND THEIR FIELD ASSAY

BY ALFRED C. LANE

This paper has been published as pages 501-512 of this volume.

The following papers were read by title:

PHOSPHATE DEPOSITS OF FLORIDA WITH RELATION TO THE UNDERGROUND WATER LEVEL

BY E. H. SELLARDS

ASBESTOS DEPOSITS OF THE GRAND CANYON, ARIZONA

BY JOSEPH HYDE PRATT

ANCIENT TECTONICS OF THE BASIN RANGES

BY CHARLES R. KEYES

ROCK-FLOOR OF INTERMONT PLAINS OF THE ARID REGION

BY CHARLES R. KEYES

Published as pages 63-92 of this volume.

The next paper read was

GLACIAL PERIODS AND THEIR BEARING ON GEOLOGICAL THEORIES

BY A. P. COLEMAN

This paper has been published as pages 347-366 of this volume. An active discussion was participated in by W. G. Tight, A. C. Lawson, I. C. White, H. M. Ami, G. K. Gilbert, H. E. Gregory, and C. R. Van Hise.

CHIEF FEATURES OF THE STRATIGRAPHY AND STRUCTURE OF MOUNT DIABLO, CALIFORNIA

BY GEORGE D. LOUDERBACK

[*Abstract*]

Mount Diablo is a distinctive feature of the central coast ranges, because it rises from low valleys on practically all sides, and is not merely a more promi-

nent peak of a continuous range. It shows a remarkably complete stratigraphic series of the characteristic Coast Range formations. Structurally it is an overturned and overthrust anticline of very late origin. There is also evidence of an earlier structural form. The geology of mount Diablo may be taken as showing a stratigraphic succession and an orogenic history characteristic of the coast ranges from the Klamath mountains to the Tehachapi.

Discussion by A. C. Lane, A. C. Lawson, and H. P. Cushing.

The following papers were then read by title:

THE EARTHQUAKE IN OWENS VALLEY, CALIFORNIA, IN 1872

BY WILLIAM HERBERT HOBBS

BEGINNING AND RECESSION OF SAINT ANTHONY FALLS

BY FREDERICK W. SARDESON

This paper was printed as pages 29-52 of this volume.

THE "NEBRASKA LOESS MAN"

BY B. SHIMEK

This paper was printed as pages 243-254 of this volume.

DISTRIBUTION OF DRUMLINS AND ITS BEARING ON THEIR ORIGIN

BY FRANK B. TAYLOR

CIRQUES AND ROCK-CUT TERRACES OF MOUNT TOBEY, MASSACHUSETTS

BY B. K. EMERSON

The next paper was

LOWER PORTION OF THE PALEOZOIC SECTION IN NORTHWESTERN NEW YORK

BY H. P. CUSHING

This paper was published as pages 155-176 of this volume. The paper was discussed by H. M. Ami.

At 12.15 o'clock the Society adjourned for luncheon in the dining-room of the university, after which President Tight led the way to the flat roof of one of the pueblo style dormitories, from which he pointed out the geological features of the surrounding country.

At 2 o'clock the afternoon session began with the reading of the annual address by the retiring President, President Charles R. Van Hise, of the University of Wisconsin, who chose as his subject "The problem of the pre-Cambrian." By request of the President, his address was thrown open to discussion, and remarks were made by A. C. Lane, A. C.

Lawson, A. P. Coleman, H. M. Ami, and C. R. Van Hise. This address was published as pages 1-28 of this volume.

The following papers were then read by title:

RED SANDSTONE FORMATION OF SOUTHEASTERN MINNESOTA

BY C. W. HALL

GEOLOGICAL HISTORY OF THE REDSTONE QUARTZITE

BY FREDERICK W. SARDESON

Published as pages 221-242 of this volume.

PALEOZOIC AND MESOZOIC OF CENTRAL WYOMING

BY N. H. DARTON

Published as pages 403-474 of this volume.

SOME FEATURES OF THE GEOLOGY OF ARIZONA AND WESTERN NEW MEXICO ALONG THE SANTA FE RAILROAD

BY N. H. DARTON

After this the Society listened to the reading of a paper on

GRENVILLE-HASTINGS UNCONFORMITY

BY WILLET G. MILLER AND CYRIL W. KNIGHT

[*Abstract*]

The crystalline limestone and associated pre-Cambrian sedimentary rocks of southeastern Ontario and the adjacent parts of the province of Quebec, to which Logan and his colleagues long ago gave the names of Grenville and Hastings series, have never been satisfactorily classified as regards their age. Recent work by the present writers has shown that much at least of what has been called the Hastings series, consisting of limestones, conglomerates, and other fragmental rocks, is much younger than, and forms a well defined unconformable series with, the typical crystalline limestones and associated fragmental rocks of what has been called the Grenville series proper. The view that the Grenville and Hastings constitute one series, the former being a more highly altered phase of the latter, is no longer tenable.

The writers find the Keewatin series of the Lake Superior region represented in southeastern Ontario by ancient rocks of like character. The Grenville limestones have been deposited on the surface of the Keewatin. The writers class the Grenville limestone as regards age with the Keewatin iron formation of lake Superior, which it has not been found possible in that region to separate from the greenstones. The pre-Cambrian conglomerate and associated sedimentary rocks overlying, uncomformably, the Grenville limestone are classed as Huronian. The conglomerate contains not only ordinary fragments of the Grenville limestone, but "eozoon"-like boulders as well, thus showing that the limestone is much older than the conglomerate. Moreover, the "pebbles of

cherty and ferruginous rocks resembling those found in the iron ranges of lake Superior" in the conglomerate of eastern Ontario are found by the writers to have been derived from layers or bands of this material in the Grenville limestone.

The paper was read by Mr. Miller and the discussion was participated in by A. P. Coleman, H. P. Cushing, C. R. Van Hise, A. C. Lane, and W. G. Miller.

The next paper was

RELATION OF THE EQUUS BEDS OF KANSAS TO REVERSED MISSISSIPPI DRAINAGE

BY W. G. TIGHT

The paper was discussed by A. P. Coleman, H. E. Gregory, A. C. Lane, and F. W. Cragin.

The following two papers were read without intermission by Dr. A. C. Lane:

NEW UPPER SILURIC FAUNA FROM SOUTHERN MICHIGAN[1]

BY W. H. SHERZER AND A. W. GRABAU

Contents

INTRODUCTORY

This fauna raises the question whether the beds from the Sylvania to the Dundee should be regarded as Silurian with precisive Devonic forms or "colonies," or whether the Sylvania should be regarded as Oriskany, and the

[1] By permission of the state geologist of Michigan.

physical conditions and fauna of the Siluric may be supposed to have lingered in Michigan longer than elsewhere.

In regard to this question entire agreement has not been reached, and there is a chance for light from new facts, but as the problem has direct bearing on certain knotty questions in New York, Canada, and Ohio, it seems well to give the ascertained paleontologic facts to help others (Lane).

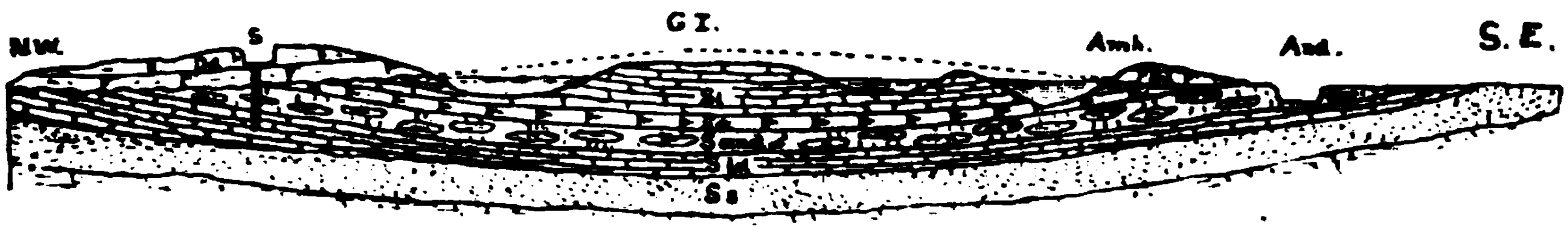

FIGURE 1.—*Section across the Detroit River*

S. Sibley quarry and bore-hole.
G. I. Grosse Isle.
Amh. Amherstburg channel.
And. Anderdon quarry.
Dd. Devonic—Dundee limestone.
Sl. Siluric—Lucas dolomite.
Sa. Siluric—Amherstburg dolomite.
Sand. Siluric—Anderdon coral limestone.
Sfd. Siluric—Flat Rock dolomite.
Ss. Siluric—Sylvania sandstone.

MONROE FORMATION

SALT SHAFT EXPOSURE AND SECTION

In December, 1906, the salt shaft of the Detroit Salt Mining and Manufacturing Company penetrated a remarkable coral reef with a coral fauna of Devonic affinities deeply embedded in the Upper Siluric strata of Michigan—the Monroe formation. The existence of this reef had been suspected from the chips of the various wells drilled in this region,[2] while many years ago T. Sterry Hunt reported a similar coral horizon at a depth in the Upper Siluric beds of Goderich, Canada. Hall identified[3] the fragments obtained from the Goderich wells with corals known otherwise only from the Onondaga limestone.

The section of the salt shaft is as follows, in descending order:

(Elevation of mouth of shaft, 575 feet above tide.)	Feet	Feet
Drift	83	83
Dundee limestone, mostly a very pure calcarenite, rich in fossils, representing the lower Middle Devonic	63	146
DISCONFORMITY:[4]		
"Lucas" dolomite, a hard, very porous dolomite of a lutaceous texture, and full of cavities left by dissolved gastropods and other fossils	189	335
Intercalated limestone (*Anderdon limestone*), containing the coral fauna. The rock is a pure calcarenite (lime sand rock), in which the corals are embedded	38	373
Flat Rock dolomite, similar to the upper dolomite, but more compact, and with few fossils	47	420
DISCONFORMITY:		
Sylvania sandstone, a pure silicarenite or quartz sand rock	117	537

[2] Michigan Geological Survey, vol. v, pt. ii, pp. 27, 28, and plates of Monroe, Mount Clemens, Port Lambton, Port Huron, etc.

[3] Transactions of the American Institute of Mining Engineers, vol. v, p. 538; also Geol. Surv. of Canada, Report of Progress, 1876-7, pp. 221-243.

[4] *The hiatus* supposed to be marked by disconformity was not very apparent in the upper shaft (Lane).

	Feet	Feet
DISCONFORMITY:		
Lower Monroe dolomites to salt, as shown by preliminary well records	334	871

ANDERDON EXPOSURE

The only exposure of the intercalated coral limestone is found on the opposite side of the river in the Anderdon quarry, in Anderdon township, Essex county, Ontario, about 2 miles east of Amherstburg and 15 miles south of Detroit.[5] It is from this locality that the formation takes its name. In the quarry about 30 feet of Dundee is shown, and immediately below it lies the Anderdon, of which about 30 feet are exposed by the quarrying operations. The contact between the Dundee and Anderdon is clearly a disconformable one, as shown not only by the absence of the 189-foot Flat Rock dolomite, which in the salt shaft at Detroit intervenes between the Dundee and Anderdon, but also by pronounced erosion features on the Anderdon. The top of this bed, where freshly uncovered by the removal of the Dundee, shows sections of large gastropod and cephalopod shells (Trochonema and Trochoceras), which were partly worn away before the Dundee was deposited on the erosion surface. Furthermore, old solution fissures in the upper surface of the Anderdon were filled by the lime sands which form the basal part of the Dundee.

In one part of the quarry the Anderdon limestone is a great coral and Stromatopora reef, while in other parts it is for the most part a finely bedded, compact calcilutite (consolidated limestone mud) with conchoidal fracture and of great purity. Analyses have shown that it contains over 99 per cent $CaCO_3$, while in compactness and texture it suggests lithographic stone.

SIBLEY CORE AND OTHER EXPOSURES OF ANDERDON

About 6½ miles northwest from the Anderdon quarry in the drill cores at Sibley the Anderdon was again found to have the coral-reef facies and to underlie directly the Dundee. Between the two on Stony Island and on Grosse Isle a brown dolomite is shown, to which further attention is invited. Some of the best exposures formerly to be found were in the old Patrick quarry, at the south end of Grosse Isle, in the Detroit river. At present the quarries at Gibraltar, 3 miles west of the Patrick quarry, furnish excellent exposures of this rock. Other good exposures are in the Woolmith quarry, near Scofield, 15 miles southwest from Gibraltar, and at Sylvania and neighboring regions in northwestern Ohio. In all these cases it lies but a short distance above the Sylvania sandstone, which indeed is shown beneath it in the Woolmith quarry and at Silica, near Sylvania, Ohio. Two divisions are generally recognizable—a lower magnesian calcarenite, with a fauna transitional between that of the Anderdon and the overlying bed, and the upper a gray dolomitic calcilutite with a gastropod fauna. This upper bed, of which from 30 to 40 feet are shown in the quarries, is the typical Lucas formation of Ohio, so named by Prosser from the outcrops in Lucas county. For convenience it may be desirable to designate the lower calcarenite by a special name, that of Amherstburg dolomite being perhaps the best available one, since this bed forms the

[5] Nattress: Ninth report of the Michigan Academy of Science, p. 177; Ontario Bureau of Mines, 1904, part II, p. 41; also report for 1902, p. 123.

bottom of the eastern channel of the Detroit river opposite Amherstburg, Ontario. Recent dredgings have brought up the rock, and from it an extensive fauna has been collected by the Reverend Doctor Nattress, of Amherstburg. The greatest thickness of the Amherstburg dolomite is probably not over 20 or 30 feet, and a part of it is seen in the lower part of the Patrick, Gibraltar, and Woolmith quarries in Michigan and the Silica and Webster quarries in the Sylvania district of Ohio.

CORRELATION OF THE BEDS

The correlation of these beds with the beds exposed in the salt shaft at Detroit is not as simple as it would at first appear. From the fact that in the quarries cited the dolomites rest directly on the Sylvania sandstone, one would be led to regard them as the equivalent of the lower or Flat Rock dolomite bed of the salt shaft, which lies between the Sylvania and the Anderdon. The fossils, however, tell a different story. There is not a single species in common between the Flat Rock dolomite of the salt shaft and the Amherstburg or Lucas beds. The Lucas, however, in all its outcrops carries a fairly abundant fauna mainly of gastropods, which is identical with that of the *upper* dolomite—189 feet thick—of the salt shaft. Moreover, the Amherstburg dolomite, which lies below the Lucas in all the quarries, contains an equal mixture of Anderdon and Lucas fossils, the former often predominating. The only possible interpretation of this seems to be that the Lucas dolomite of the quarries represents the lower part of the upper dolomite bed of the salt shaft, which therefore should be referred to as the Lucas, and that the Amherstburg dolomite lies between the Lucas and the Anderdon, forming a transitional bed. The Amherstburg bed has not been distinguished in the salt shaft, which is not surprising when the small size of the shaft is considered.

If the above interpretation is correct, some surprising facts with reference to the structural geology of southern Michigan and the adjoining areas are revealed. It is first of all shown that the Upper Monroe beds overlap southward against the Sylvania sandstone as against a basal bed. This would indicate that before the formation of the Upper Monroe beds the area involved was dry land. Studies of the authors on the Sylvania sandstone now in progress reveal facts which point to æolian or anemoclastic origin of this sandstone. Another harmonious fact is found in the thickening of the Flat Rock dolomite of the salt shaft as we go northward, as shown by well records (see diagram figure 1).

Another surprising fact is that in pre-Dundee time a number of low folds extended across southeastern Michigan, Canada, and Ohio in a direction east-northeast. A synclinal trough extended through the center of Grosse isle, past the Gibraltar, Flat Rock and Woolmith quarries, probably a little to the north of all of these. An anticlinal axis extended parallel to this through the Anderdon quarry and through the region where now are situated the Sylvania sand-pits south of Scofield. A second anticlinal axis, also parallel or approximately so to the others, extended through the region of the present Sibley quarries, or somewhat to the north. Peneplanation during Lower Devonic time truncated these low folds, so that on the deposition of the mid-Devonic Dundee the base of this formation came to rest on different members of the Upper Siluric. Thus at the Anderdon quarry the bed exposed by the truncation of the anti-

cline was the Anderdon, and on this came to rest the Dundee (see diagram, figure 1). In the southwestward extension of this same fold the bed exposed at the top of the truncated anticline was the Sylvania, the axis of the anticline here having crossed to the south of the line of overlap—that is, the shoreline at the end of Anderdon time. At this point the Dundee came to rest directly on the Sylvania, remnants of it being still visible in intimate association with the Sylvania. This intimate association of the two caused Rominger to mistake the Sylvania for the Oriskany. South of this axis the Dundee came to rest again on the Lucas beds, as shown in several quarries in the vicinity of Sylvania, Ohio. This section formed the southern flank of the Anderdon-Tollpit anticline. Since the line of overlap of the Amherstburg over the Anderdon—that is, the shoreline at the end of Anderdon time—curves more to the south than does the axis of the anticline (extending from the Gibraltar quarry and the region south of Amherstburg through the Woolmith quarry and thence curving south to the Silica and Webster quarries near Sylvania), it is evident that the resultant outcrops will be quite varied.

POSSIBLE ECONOMIC VALUE

Incidentally it may be remarked that these anticlines may have an economic value, since all the lower strata are involved, and favorable conditions for the storage of oil and gas thus created. The fact that these anticlinals could have been located only with the help of paleontology seems, in view of what is known of the connection of oil and gas with such structures, an interesting illustration of the practical value of the study of the fossils.

PROOF OF THE LOWER DEVONIC HIATUS

The foregoing discussion has made clear that a hiatus of considerable magnitude exists between the Monroe beds and the overlying Dundee limestone, the approximate equivalent of the Onondaga limestone of New York. At the salt shaft this limestone rests on 189 feet of Lucas dolomite. At the Sibley and the Anderdon quarries it rests on Anderdon limestone. Between the two on Grosse Isle and Stony island lower Lucas is present; at the Gibraltar and Woolmith quarries the Dundee, now removed, formerly rested on less than a hundred feet of Lucas. Three to 4 miles southeast from the latter locality the Dundee rests on the Sylvania, and fossils of the former occur in the reworked upper portion of the latter. Near the Silica and Webster quarries and at the S. K. Cooper quarry, near Sylvania, Ohio, the Dundee rests again on lower Lucas. Further southeast in Ohio the Dundee (Columbus) rests on various members of the Lower Monroe,[6] while at Buffalo, New York, the Onondaga rests on the lower 7 feet of the Bullhead or Akron limestone, the probable equivalent of the Amherstburg bed of Michigan and the Cobleskill of eastern

[6] "Relative to the lower 35 or 40 feet of the Columbus limestone, permit me to add a word: In central Ohio the dividing line between this 'brown saccharoidal magnesian limestone' and the underlying Monroe formation, with its banded compact drab limestone, is very distinct. In fact, it is an unconformity [disconformity], and at many places the lower portion of the brown limestone (Columbus) is a real basal conglomerate. From this 40 feet of brown limestone I have collected a rather scanty Columbus limestone fauna, even in the basal layers. At Sandusky and vicinity the unconformity [disconformity] is also evident. Here the upper part of the Monroe formation carries a

New York. A period of dry land is thus indicated for Michigan, Ohio, and western New York and Canada, and elsewhere as well, during which prolonged erosion occurred, preceded by a basining of the Michigan and doming of the Cincinnati regions, and the formation of the diagonal folds in southeastern Michigan and Canada. It was during this same period of dry land condition that the extensive brecciation of the Monroe beds occurred, through subærial agencies, producing the large and small angular fragments, which were subsequently, on the advent of the mid-Devonic Dundee sea, incorporated in the base of that formation, as now found at Mackinac island and Goderich, Canada, and outlined by Grabau before this Society during a former meeting.

Synopsis of the Faunas of the Monroe Beds of Michigan, Ontario, Ohio, and western New York

The Lower Monroe Faunas

In general.—In the following annotated list all the species which have so far been obtained from the Monroe formation are given. They are fully described and illustrated in a memoir of this fauna (by Grabau), now awaiting publication at the hands of the Michigan Geological Survey, and forming part of an extensive discussion of the Monroe formation by the present authors. Although the majority of species are new, and their full characterization can not be given here, it is nevertheless deemed advisable to list them, with brief suggestions of their affinities.

Although the discussion of the Lower Monroe formation does not enter into the present paper, it is nevertheless deemed desirable to include a list of the faunæ, since this will serve to emphasize the distinctness of the faunæ of the Upper Monroe beds. The subdivisions here used are those discussed in another paper by Lane, Prosser, and the present authors, and adopted in the memoir on the Monroe formation already referred to.

A. Fauna of the Greenfield dolomite.—This horizon is so far known only from Ohio, where it is exposed at Greenfield and Ballville. The fauna was originally described by Whitfield, though many of his identifications can not now be accepted. The type material is mostly in the collection of Columbia University.

Brachiopoda:

1. *Schuchertella hydraulica* (Whitfield), characterized by alternation of coarser with several finer radii; very common.
2. *Camarotœchia hydraulica* (Whitfield).

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fauna which fixes its age, while immediately above these layers comes a limestone filled with a rich Columbus fauna, thus making a clear case of it for central Ohio.

"West of Toledo, however, the dividing line is not so evident between the Lucas dolomite and the base of the Columbus limestone, as we consider it in northwestern Ohio.

"The following measurements are copied from my field book:

Columbus limestone	
Lucas dolomite	
Compact, drab dolomitic limestone, banded	63 feet
Drab dolomitic limestone, with some gray or brown sandstone layers alternating	36 feet
Sylvania sandstone	

"C. R. Stauffer, in discussion."

3. ***Rhynchospira præformosa*** Grabau manuscript = *Retzia formosa* Whitfield non Hall.
4. ***Hindelia ? whitfieldi*** Grabau manuscript = *Meristella bella* Whitfield in part; common.
5. ***Hindella rostralis*** Grabau manuscript = *Meristella bella* Whitfield in part.
6. ***Hindella ? rotundata*** (Whitfield) = *Nucleospira rotundata* Whitfield.
8. ***Whitfieldella subsulcata*** Grabau manuscript, a rather rare form, related to *W. sulcata*.

OSTRACODA:

9. ***Leperditia angulifera*** Whitfield.
10. ***Leperditia altoides*** Grabau manuscript, larger and more robust than *L. alta*.

B. Fauna of the Put-in-bay dolomites.—This is best known from Put-in-bay island, lake Erie, but has also been found on the main land.

1. ***Spirifer ohioensis*** Grabau manuscript (*Sp. vanuxemi* Whitfield, a larger species than *S. vanuxemi* Hall, with fewer and coarser plications, the inner very broad; common).
2. ***Goniophora dubia*** (Hall), abundant.
3. ***Leperditia alta*** Conr., abundant.
4. ***Eurypterus eriensis*** Whitfield.

C. Fauna of the Raisin River beds.—These beds are partly exposed on Put-in-bay island, but more extensively in southeastern Michigan and adjoining portions of northern Ohio. Fossils are not very numerous.

1. ***Whitfieldella prosseri*** Grabau manuscript (*Meristella lævis* Whitfield, the most abundant and characteristic form).
2. ***Pholidops*** cf. *ovata* Hall; rare.
3. ***Camarotœchia*** sp.
4. ***Meristina profunda*** Grabau manuscript and mutation *sinosus* Grabau manuscript.
5. ***Pterinea lanii*** Grabau manuscript (*Pt. aviculoidea* Whitfield non Hall; a common species).
6. ***Goniophora dubia*** Hall. Very rare.
7. ***Tellinomya*** sp.
8. ***Modiomorpha*** sp.
9. ***Cœlidium*** ? cf. *minutum* Hall.
10. ***C.*** ? cf. *extenuatum* Con.
11. ***Loxonema*** sp.
12. ***Holopea*** sp. 1.
13. ***Holopea*** sp. 2.
14. ***Holopea*** sp. 3.

(12–14) Three clearly distinct species, but too poorly preserved for specific identification.

15. ***Spirorbis laxus*** Hall. An abundant species.
16. ***Beyrichia*** cf. *sussexensis* Weller. Rare.
17. Plant remains.

THE UPPER MONROE SERIES

D. Fauna of the Flat Rock dolomite of the salt shaft.—This fauna is known from the salt shaft, but some fossils have also been found in the dolomite of Flat Rock which represents this horizon.

1. ***Syringopora*** cf. *hisingeri* Bill. This species is doubtfully identified from the salt shaft and from Flat Rock.
2. ***Syringopora cooperi*** Grabau manuscript, a species with numerous short transverse processes, somewhat whorled. *S. compacta* Bill., from Anticosti, seems to be a related form.
3. ***Favosites*** cf. *maximus* Troost. Identified with a specimen from the Onondaga of Ohio, referred to this species.

E. Fauna of the Anderdon bed of the salt shaft (*ss*) *and the Anderdon quarry* (*a.q.*).—Unless specified, the species occurs in both localities.

STROMATOPOROIDS:

1. ***Clathrodictyon ostiolatum*** Nicholson, abundant; a Guelph and Cobleskill species.
2. ***Stromatopora galtense*** (Dawson), abundant; a Guelph and Cobleskill species.
3. ***Stylodictyon sherzeri***, Grabau manuscript, *ss.*, the only Siluric representative of the genus known; closely related to species from the Columbus limestone and from the Traverse beds of Michigan.
4. ***Clathrodictyon variolare*** v. Rosen, *aq.;* a Siluric type, rather common.
5. ***Cœnostroma pustulosum***, Grabau manuscript, *aq.;* an abundant form.
6. ***Idiostroma nattressi***, Grabau manuscript. A small branching species, closely similar to, if not identical with those abounding in the Traverse group of Michigan.

ANTHOZOA:

7. ***Helentorophyllum caliculoides*** Grabau manuscript, gen. et sp. Like *Enterolasma caliculum*, of the Niagara, but with carinæ on the septa; not uncommon; *aq.*
8. ***Cyathophyllum*** cf. ***thoraldense*** Lambe; rare; *ss.*
9. ***Cyathophyllum americanum***, mut. *anderdonense* Grabau manuscript. Differs from the species in its somewhat more concentrated large cysts; common; *aq.*
10. ***Synaptophyllum multicaule*** (Hall).
11. ***Diplophyllum integumentum*** Barrett. A characteristic species of the Decker ferry beds of New Jersey; common.
12. ***Ceratopora tenella*** (Rominger); common; *aq.*
13. ***Favosites basaltica*** var. ***nana*** Grabau manuscript; common; *ss.;* a form differing in nothing but size of corallites from the typical Columbus limestone species.
14. ***Favosites rectangularis*** Grabau manuscript; common; a digitate species with the corallites turning at nearly right angles. The species has squamulæ like the Devonic species.
15. ***Cladopora bifurcata*** Grabau manuscript; an abundant form of Siluric affinities.
16. ***Favosites concava*** Grabau manuscript; a common form; *aq.*
17. ***Syringopora microfundulus*** Grabau manuscript; not unlike *S. infundibulum* Whitfield, but very much smaller; rare; *ss.*

BRACHIOPODA:

18. ***Prosserella modestoides*** Grabau manuscript; gen. et sp. A genus which so far appears to be confined to the Upper Monroe; is characterized among other features by two strong but closely parallel, rarely uniting septa in the pedicle valve. Its nearest allies are found in the Middle Devonic of Europe. *P. modestoides* is common in *ss.*, is large for the genus, and non-plicate; a related form apparently occurs in the Guelph.
19. ***Prosserella lucasi*** Grabau manuscript; rare, but abundant in Lucas dolomite.

PELECYPODS:

20. ***Conocardium monroense*** Grabau manuscript; a species very closely related to *C. trigonalis* of the Schoharie grit; common.

GASTROPODS:

21. ***Eotomaria galtensis*** (Billings)?; an impression referred to this species *ss.*
22. ***Pleurotomaria*** cf. ***velaris*** Whiteaves; an imperfect form of this type.

F. Fauna of the Amherstburg bed.—This is best known from the dredging in the Detroit river opposite Amherstburg, Ontario, where the Reverend Mr Nattress made an extensive collection. It is also known from the Patrick, Gibraltar, and Woolmith quarries.

STROMATOPOROIDS:

1. *Clathrodictyon ostiolatum* Nicholson; often in large, digitate masses.

ANTHOZOA:

2. *Heliophrentis alternata* Grabau manuscript, gen. et sp. A Zaphrentoid coral with carinæ in the upper part of the septa; a derivative of Siluric Zaphrenti; common. A closely related if not identical species occurs in the Schoharie.
3. Mutation *compressa* Grabau manuscript.
4. Mutation *magna* Grabau manuscript.
5. *Heliophrentis carinata* Grabau manuscript, with septa carinated throughout greater part of calyx; common.
7. *Cystiphyllum americanum* mut. *anderdonense* Grabau manuscript; rather rare.
8. *Acervularia* sp. nearest to *A. rugosa* of the Onondaga.
9. *Synaptophyllum multicaule* (Hall).
10. *Diplophyllum integumentum* Barrett; rather rare.
11. *Romingeria umbellifera* (Bill.); indistinguishable from the Devonic form.
12. *Ceratopora regularis* Grabau manuscript.
13. *Favosites tuberoides* Grabau manuscript; differs from the Devonic *F. tuberosus* only in the smaller corallites, which have well-marked squamulæ.
14. *Cladopora bifurcata* Grabau manuscript; abundant.
15. *Cladopora* cf. *cervicornis* Hall; poorly preserved, but with all the characters of that species.
16. *Syringopora microfundulus* Grabau manuscript. ?
17. *Syringopora* cf. *hisingeri* (Bill.). ?

BRYOZOA:

18. *Fenestella*, two sp.

BRACHIOPODA:

19. *Schuchertella interstriata* (Hall); common.
20. *S. amherstburgense* Grabau manuscript; rare.
21. *Stropheodonta vasculosa* Grabau manuscript; closely related to *S. patersoni-bonamica* Clarke of the Helderbergian.
22. *Stropheodonta demissa* mut. *homolostriata* Grabau manuscript; like some Onondaga forms of *S. demissa*.
23. *Stropheodonta preplicata* Grabau manuscript; closely related to *S. plicata* of the Traverse group.
24. *Stropheodonta* sp.
25. *Spirifer sulcatus* mut. *submersus* Grabau manuscript; of the type of the European *S. sulcatus*.
26. *Prosserella modestoides* Grabau manuscript.
27. *P. modestoides* mut. *depressus* Grabau manuscript; common.
28. *P. subtransversa* Grabau manuscript; possibly referable to the Lucas.
29. *Whitfieldella* sp.
30. *Meristospira michiganense* Grabau manuscript, gen. et sp. Hinge structure combining characters of *Merista* or *Whitfieldella* and *Nucleospira*; abundant in Woolmith quarry.
31. *Meristina profunda* Grabau manuscript; doubtfully identified.
32. *Atrypa reticularis* Linn.; a single fragmentary impression.
33. *Cyrtina* sp.
34. *Orthid brachiopod*.

PELECYPODA:

35. *Panenka canadensis* Whiteaves; a common form most nearly like the Schoharie type; described by Whiteaves as a mid-Devonic form.
36. *Cypricardinia canadense* Grabau manuscript.
37. *Conocardium monroense* Grabau manuscript; abundant and characteristic.

GASTROPODA:

38. *Hormotoma subcarinata* Grabau manuscript; most nearly related to Gotlandian species; most characteristic of the Lucas.
39. *Holopea antiqua* var. *perrctusta* (Conrad).
40. *Acanthonema holopiformis* Grabau manuscript, gen. et sp.; a moderately high-spired form like Orthonema, but with nodulated spirals.
41. *Strophostylus cyclostomus* Hall; rather common.
42. *Eotomaria areyi* Clarke and Ruedemann; rather common.
43. *Eotomaria* sp.
44. *Lophospira bispiralis* (Hall); rather common.
45. *Trochonema ovoides* Grabau manuscript; a large flat-spired form; nearest ally in Helderbergian.
46. *Hercynella canadense* Grabau manuscript; the first species of this characteristic Hercynian gastropod found in America; it is most nearly related to *H. fastigiata* Barrande.

CEPHALOPODA:

47. *Dawsonoceras annulatum;* a strongly annulated variety.
48. *Cyrtoceras orodes* Bill.; identical with species described by Clarke and Ruedemann from the Guelph.
49. *Poterioceras* cf. *sauriens* Clarke and Ruedemann; apparently identical with the Guelph species.
50. *Trochoceras anderdonensis* Grabau manuscript; a smooth-shelled and loose-spired form closely similar to *T. priscum* Barr. of the Bohemian Siluric.

ANNELIDA:

51. *Cornulites armatus* Conr.; a species also characteristic of the Guelph.

TRILOBITÆ:

52. *Prœtus crassimarginatus* Hall; several cephala and pygidia and a nearly entire specimen, indistinguishable from the characteristic Schoharie form.

G. Fauna of the Lucas dolomite.—This is exposed in the salt shaft and in numerous quarries of southern Michigan and Lucas county, Ohio.

ANTHOZOA:

1. *Heliophrentis carinata* Grabau manuscript; rare in this horizon.
2. *Cylindrohelium profundum* Grabau manuscript, gen. et sp.; in general like Diplophyllum, but with carinæ; calyx profound and parallel-sided. The most characteristic corals of this horizon, found also in corresponding horizon of the Saskatchewan region, upper Canada.
3. *Cylindrohelium heliophylloides* Grabau manuscript; more irregular and with shorter calyx, and with stronger carinated septa; *ss.;* an identical form figured by Clarke and Ruedemann as Heliophyllum sp. from the Guelph.
4. *Cladopora bifurcata* Grabau manuscript; not uncommon.

BRACHIOPODA:

5. *Schuchertella interstriata* (Hall); not uncommon.
6. *Camarotœchia semiplicata* (Conrad); a rather common species in the *ss.*
7. *Spirifer sulcata,* mut. *submersa* Grabau; rare in the Lucas.
8. *Sp. modestus* Hall; not uncommon in the *ss.*
9. *Prosserella lucasi* Grabau manuscript; an abundant form with pronounced fold and sinus.
10. *Prosserella subtransversa* Grabau manuscript; a transverse form with plications; common.
11. *Prosserella unilamellosus* Grabau manuscript, with the dental lamellæ united into a median septum at the base.
12. *P. planisinosus* Grabau manuscript; a large species with shallow, flat-bottomed but pronounced median depression; rare.

PELECYPODA:

13. *Panenka canadensis* Whiteaves; rare in the Lucas.
14. *Pterinea bradti* Grabau manuscript; a low, long-winged type common in the ss.
15. *Goniophora* sp.
16. *Conocardium monroense* Grabau manuscript; less common than in the lower beds.
17. *Modiella* ? sp.

GASTROPODA:

18. *Hormotoma subcarinata* Grabau manuscript; abundantly represented.
19. *H. tricarinata* Grabau manuscript; a derivative of the preceding, with an additional carina.
20. *Cœlidium* ? *minutum* Hall; doubtfully identified.
21. *Cœlidium extenuatum* Hall; ? doubtfully identified.
22. *Loxonema parva* Grabau manuscript; a small species.
23. *Holopea subconica* Hall; common in salt shaft.
24. *Poloumita* cf. *crenulata* Clarke and Rued.; of the type of the Guelph form.
25. *Pleurotrochus bicarinatus* Grabau manuscript, gen. et sp.; type similar to the strongly spinose "Murchisonia" of the Upper Siluric of Gotland, of which several are referred to this genus.
26. *Acanthonema holopiformis* Grabau manuscript; a short, close-coiled form with two nodose spirals; common.
27. *A. holopiformis* var. *obsoleta* Grabau manuscript, with middle spiral non-nodose, obsolete.
28. *Acanthonema laxa* Grabau manuscript; longer and more loosely coiled; common.
29. *Acanthonema newberryi* (Meek) (*Orthonema newberryi* Meek), described as occurring in the Devonic.
30. *Pleuronotus subangulatus* Grabau manuscript; recalls strikingly the Devonic *P. decewi*.
31. *Euomphalus* cf. *fairchildi* Clarke and Ruedemann; rare in *ss*.
32. *Eotomaria areyi* Clarke and Ruedemann; fairly abundant.
33. *Eotomaria galtensis* (Bill.); characteristic and not uncommon.
34. *Euomphalopterus* cf. *valeria* (Bill.); a characteristic fragment from the *ss*.

CEPHALOPODS:

35. *Orthoceras* (Protokionoceras) cf. *trusitum;* several fragments showing the characteristic features of this Siluric species.

H. The fauna of the Bullhead or Akron dolomite of western New York.—This was originally described by Grabau, but some revision is necessary.[7]

ANTHOZOA:

1. *Cyathophyllum* (?) *hydraulicum* Simpson; common.
2. *Favosites* sp.

BRACHIOPODA:

3. *Schuchertella interstriata* (Hall); an abundant and characteristic form.
4. *Spirifer eriensis* Grabau.
5. *Whitfieldella sulcata* (Vanuxem).
6. *Whitfieldella subsulcata* Grabau manuscript (*Whitfieldella* cf. *levis* (Whitf.) Grabau).
7. *Whitfieldella* sp. (*Whitfieldella* cf. *rotundata* (Whit.) Grabau).
8. *A. rhynchonelloid.*

GASTROPODA:

9. *Loxonema* ? sp.
10. *Pleurotomaria* ? sp.

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[7] The name Akron dolomite is derived from its exposure in the village of Akron, in Erie county, New York. It is approximately equivalent to the Cobleskill of the East.

CEPHALOPODA:

11. *Trochoceras (Mitroceras) gebhardi* Hall.

OSTRACODA:

12. *Leperditia scalaris* Jones; common.

PLANTÆ:

13. *Nematophytum crassum* Penhallow; rare.
14. *Buthothrephis clavelloides* Grabau manuscript; rare.

Schuchertella interstriata, *Spirifer eriensis*, *Mitroceras gebhardi*, and *Leperditia scalaris* link this fauna with the Cobleskill. *Schuchertella interstriata* and the *Whitfieldellas* link it with the Amherstburg.

DISCUSSION OF THE FAUNAL DIFFERENCES

A survey of these faunas brings out the remarkable fact that there is nothing in common (a few doubtfully identified gastropods excepted) between the Lower and Upper Monroe. So distinct are the faunas that they may be considered as derived from widely separated provinces. The Lower Monroe is apparently an Atlantic fauna or series of faunas, and we are led to believe that an embayment from the Atlantic extended as far as Wisconsin in post-Salina time, and that the successive members of the Lower Monroe were deposited in this. The marine "Salina" described by Schuchert from Maryland most probably belongs here, the path of invasion being approximately across that region. There appears to be nothing in New York which corresponds to this series, that state being apparently north of the embayment. The embayment covered Ohio, Michigan, and probably a part of Indiana, and extended into Wisconsin.

Following the deposition of the Lower Monroe came a retreat of the sea and æolian deposits of quartz sands accumulated upon the limestone foundation. These are now seen in the Sylvania sandstone, the source of the material of which probably was the Saint Peter sandstone. The Upper Monroe invasion was from the northwest, and it brought with it a wholly new fauna, in which the prevailing element was of Devonic aspect. A large proportion of the species of the Anderdon and Amherstburg beds is most nearly related to the Schoharie fauna, the similarity being often so great that species have been described as Schoharie or Onondaga forms.

The following are the species more nearly related to mid-Devonic forms than to known Siluric:

STROMATOPOROIDS:

1. *Stylodictyon sherzeri* cf. *S. columnare*.
2. *Idiostroma nattressi* cf. *I. traversense* Grabau manuscript.

ANTHOZOA:

3. *Heliophrentis alternatum* cf. unidentified Schoharie form.
4. Mutation *compressa* and Mut. *magna* cf.
5. *H. carinata*.
6. *Cystiphyllum americanum*, Mut. *anderdonense* cf. *C. americanum*.
7. *Acervularia* sp. cf. *A. rugosa*.
8. *Romingeria umbillifera*, *R. umbillifera*.
9. *Ceratopora regularis*.
10. *Favosites basaltica nana* cf. *F. basaltica*.

11. *F. rectangulus.*
12. *F. tuberoides* cf. *F. tuberosus.*
13. *Cladopora* cf. *cervicornis* cf. *C. cervicornis.*
14. *Syringopora* cf. *hisingeri* cf. *S. hisingeri.*
15. *Favosites concava.*
16. *F.* cf. *maximus* cf. Devonic specimens.

BRACHIOPODA:

17. *Stropheodonta vasculosa* cf. *S. patersoni* mut. *bonamica.*
18. *S. demissa homolostriata* cf. *S. demissa* var.
19. *S. preplicata* cf. *S. plicata.*
20. *Prosserella modestoides* and mutation *depressa* cf. Devonic Spirifers of the Eifel.
21. *Prosserella lucasi.*
22. *P. subtransversa.*
23. (*P. unilamellosus*) cf. Devonic Spirifers of Europe.
24. (*P. planisinosus*).

PELECYPODA:

25. *Panenka canadensis* cf. *P. dichotoma.*
26. *Conocardium monroense* cf. *C. cuneus.*

GASTROPODA:

27. *Trochonema ovoides.*
28. *Hercynella* cf. *H. fastigiata* Barr.

TRILOBITÆ:

29. *Prœtus crassimarginatus, P. crassimarginatus.*

This list of species shows that the Anderdon-Amherstburg fauna is most nearly related to the Schoharie fauna of eastern New York, and that it probably represented the stock from which that fauna was derived. Coral reef conditions existed in Michigan and Ontario at that period, the eastern extension of these conditions being first manifested in the waterlime deposits, and later in the Akron, and finally in the Cobleskill. This latter marks the period of reestablishment of connection with the Atlantic, and we find that this formation is especially characterized by an Atlantic fauna in its more eastern development (Halysites, etcetera). The faunas mingled in the neighborhood of the Schoharie region.[8]

With the opening of the Atlantic connections the late Siluric Gastropod and Cephalopod fauna entered this region and became characteristic of the succeeding Manlius-Lucas deposits, while the typical Anderdon fauna soon disappeared. A comparison of the Anderdon and the Lucas fauna shows scarcely a common species. In the Amherstburg, however, there is more or less of the commingling of the two faunas. That the junction with the Atlantic was effected while the Amherstburg beds were forming is shown by Siluric gastropod and cephalopod elements in its fauna, and their absence from the Anderdon fauna. The correlation of the Amherstburg and Cobleskill thus seems evidenced.

Considering the Anderdon fauna as a whole, we see a blending of types of the Siluric with those of Devonic affinities. Recognizing that this fauna is interpolated between two Siluric faunæ, we are forced to admit that here is an example coming perilously near satisfying the demands of Barrande's theory

[8] A. W. Grabau: Bulletin of the New York State Museum, p. 131.

of colonies. Somewhere the Siluric fauna must have developed into the Devonic, while in other regions the Siluric fauna still lingered. That this Devonic aspect is that of the mid-Devonic fauna of America rather than the lower, shows that this evolution was progressing along different lines from that of the Helderbergian fauna. This latter fauna is alien to North America, as is well known, having come to us from Europe. Somewhere in northwestern America an indigenous Lower Devonic fauna existed, which in turn gave rise to the Middle Devonic faunas of America. This indigenous American Lower Devonic must have been much like the Middle Devonic fauna, seeing that the indigenous Upper Siluric is already so far advanced as to have a decided mid-Devonic aspect.

It might, of course, be argued that the Upper Monroe is the indigenous Lower Devonic of America and that it existed contemporaneously with the Helderbergian fauna. On such an interpretation the Sylvania marks the Siluro-Devonic hiatus, and the upper hiatus representing the folding and erosion of the entire of Monroe and earlier rocks falls into the Oriskany. That period, as we know it, was scarcely long enough for the accomplishment of such extensive erosion as is implied in the pre-Onondaga hiatus, though it is known that a considerable amount was accomplished during that time. The strongest argument against such an interpretation is, however, the Siluric character of the fauna of the Lucas dolomite and the evident correspondence of the Amherstburg and Cobleskill horizons.

NOMENCLATURE AND SUBDIVISION OF THE UPPER SILURIC STRATA OF MICHIGAN, OHIO, AND WESTERN NEW YORK

BY A. C. LANE, CHARLES S. PROSSER, W. H. SHERZER, AND A. W. GRABAU

[*Abstract*]

Contents

THE MONROE FORMATION

LOCATION AND GENERAL CHARACTERS

The highest Siluric strata of America are represented by the Monroe formation of Michigan, using this term in its limited sense for the post-Salina Siluric.

The Monroe formation is a strictly marine series succeeding the abnormal (non-marine [Grabau]) Salina. It is traceable throughout lower Michigan, westward into Wisconsin, and eastward through Ohio, Ontario, and into western New York. Where recognizable a strong dividing line separates the lower from the upper part, and in general this division is emphasized by the occurrence of the Sylvania sandstone, a rock of pure quartz grains, and representing, according to Grabau and Sherzer, an æolian deposit formed under conditions similar to those now found in the Lybian desert. According to this interpretation, the Sylvania sandstone represents a long time interval the depositional marine equivalent of which is still unknown. This long interval is further emphasized by the entire distinctness of the faunæ of the lower and upper divisions of the Monroe.

The subdivisions recognized so far in the Monroe, with their faunal characteristics (determined by Grabau), are as follows:

I. THE LOWER MONROE

Proposed name—Bass Islands series.—For this stratigraphic unit the name *Bass Islands series* is proposed, from the group of islands of that name in western Lake Erie. No other appropriate term seems to be available, though characteristic exposures of all the divisions are not found in these islands.

a. The Greenfield dolomite.—This term was proposed by Grabau in 1898, though previously used in a commercial sense, for the dolomite found about Greenfield, Highland county, Ohio, and exposed again in the regions about Ballville, in northern Ohio. The name is here accepted for this division, which is characterized by *Schuchertella hydraulica* (Whitfield); *Hindella ? whitfieldi* Grabau; *H. ? rostralis* Grabau; *Leperditia*, etcetera. The faunal zone may be called that of *Schuchertella hydraulica*. The thickness is 100 feet or more and the formation is the lowest known subdivision of the Monroe.

b. The Tymochtee shales and limestones.—This name was proposed in 1873 by N. H. Winchell for the shales and thin-bedded calcilutytes of the Monroe (Waterlime) series exposed in the creek of that name in Crawford township, Wyandot county, Ohio. The thickness there is something over a hundred feet, but the relation to the overlying and underlying formation is unknown. Its fauna likewise is unknown, and the formation must be considered a tentative division of the Lower Monroe. It is not impossible that it represents in part one or more members recognized elsewhere.

c. The Put-in-bay dolomites.—This name is proposed for the extensive fossiliferous series of waterlime exposed on Put-in-bay island, one of the Bass islands, and characterized by the fauna comprising *Spirifer ohioensis* Grabau, *Goniophora dubia* Hall, *Eurypterus eriensis* Whitfield, and Leperditia. From the abundance of the pelecypod, the paleontologic zone may be called that of *Goniophora dubia*. Something over a hundred feet of strata is exposed on Put-in-bay island, where the higher beds are in contact with the succeeding zone. The formation is also known from Marion county, Ohio. Its thickness is over 100 feet, but the base is unknown.

d. The Raisin River dolomites.—This name is proposed for the highest division of the lower Monroe exposed in Lucas and Wood counties, Ohio, and in Monroe county, Michigan, especially along the Raisin river. It is perhaps 200 feet thick and contains several oolite zones. Its known fauna comprises nearly

20 species, of which the most significant are *Whitfieldella prosseri* Grabau and *Pterinea lanii* Grabau. These are restricted to this horizon, so far as known. *Spirorbis laxus* and numerous minute gastropods, besides plant remains, further characterize this horizon. From the abundance of the brachiopod mentioned, which is everywhere found and characteristic, the faunal zone is designated as that of *Whitfieldella prosseri*.

II. THE MIDDLE MONROE

This is represented in Michigan only by the Sylvania sandstone. This is believed to represent a long interval at the end of which a new series of faunæ invaded this region upon resubmergence. The thickness of the Sylvania seldom exceeds 150 feet.

III. THE UPPER MONROE

Proposed name—Detroit River series.—For this stratigraphic unit, the group name *Detroit River series* is here proposed from the exposure of all its members along that stream. It comprises four subdivisions or faunal zones.

a. The Flat Rock dolomites.—These are exposed at Flat Rock on the Huron river, and are also found in the lower part of the salt shaft at Oakwood, near Detroit. The fauna so far obtained is meager, comprising only the corals *Syringopora cooperi* Grabau, *S.* cf. *hisingeri* Billings, and *Favosites* cf. *maximus* Troost. The first mentioned seems to be characteristic and restricted to it, and the zone is provisionally called the *Syringopora cooperi* zone. The thickness of the formation varies from 40 to 150 feet or more.

b. The Anderdon limestone.—This name, suggested by the Reverend Thomas Nattress, was adopted by Sherzer and Grabau for the coral reef limestone exposed in the Anderdon quarry, Essex county, Ontario, two miles from Amherstburg, Ontario, and in the salt shaft at Oakwood, Detroit. Its thickness is from 40 to 50 feet and its fauna a rich coral and stromatopora fauna. It varies from a pure calcilutyte to a moderately coarse calcarenyte. Six species of stromatoporoids and eleven of coral have been determined by Grabau. Among the former *Stylodictyon sherzeri* Grabau and *Idiostroma nattressi* Grabau are characteristic and restricted. From the abundance of the latter the faunal zone may be named the *Idiostroma nattressi* zone. Favosites of Devonic affinities are characteristic.

c. The Amherstburg bed.—This name is proposed by Sherzer and Grabau for the next higher stratum—a dolomite not over 20 feet thick and forming a transition zone to the overlying Lucas. This zone is rich in fossils, 52 species having been identified by Grabau, most of them being new and of Devonic affinities. The fauna unites the Anderdon and Lucas elements to a certain degree. *Panenka canadensis* Whiteaves, though not absolutely restricted to it, is its most characteristic fossil, and may serve to name the zone. The genus *Heliophrentis* Grabau is further characteristic and distinctive, while *Schuchertella interstriata* links it with the Bullhead (Akron) dolomite of western New York, this and the Cobleskill being its eastern extension. Stropheodontas of Devonic aspect further characterize the faunæ. In common with the Anderdon, it has an abundance of *Conocardium monroense* Grabau, which is the zone fossil of the two formations combined. The Spiriferoid genus, *Prosserella* Grabau, has species in the three upper members of the Upper Monroe to which it is restricted (Prosserella horizon).

d. The Lucas dolomite.—This name was proposed by Prosser in 1903 for the upper dolomites so well exposed in Lucas county, Ohio. Here they mostly rest directly on the Sylvania, the other beds being cut out by overlap. The fauna is rich and peculiar, European types of gastropods predominating. The genus *Acanthonema* Grabau, though represented in the Amherstburg, is most characteristic, and the faunal zone may be designated the Acanthonema zone. Its thickness varies up to 200 feet or over. *Cylindrohelium profundum* is restricted to it, and may be regarded as another good zone fossil.

Proposed Classification

The proposed classification in tabular form is as follows:

Upper Monroe or Detroit River Series (L., P., S., and G.) Zone of Prosserella.	*d.* Lucas dolomite (Prosser). (Zone of *Cylindrohelium profundum* and *Acanthonema*.) *c.* Amherstburg dolomite (Sherzer and Grabau). (Zone of *Panenka canadensis*.) *b.* Anderdon limestone (Nattress). (Zone of *Idiostroma nattressi*.) *a.* Flat rock (Lane, Prosser, Sherzer, and Grabau). Zone of *Syringopora cooperi*.
....	Disconformity.
Middle Monroe	Sylvania sandstone.
....	Disconformity.
Lower Monroe or Bass Islands Series (L., P., S., and G.) Zone of Leperditia.	*d.* Raisin river dolomite (Lane, Prosser, Sherzer, and Grabau). (Zone of *Whitfieldella prosseri*.) *c.* Put-in-bay dolomite (Lane, Prosser, Sherzer, and Grabau). (Zone of *Goniophora dubia*) *b.* Tymochtee beds (N. H. Winchell). *a.* Greenfield dolomite (Grabau). (Zone of *Schuchertella hydraulica*.)

The papers were discussed by A. C. Lawson, A. P. Coleman, A. M. Miller, H. M. Ami, I. C. White, and A. C. Lane.

The concluding paper of the afternoon was

STRUCTURE AND STRATIGRAPHY OF THE OUACHITA ORDOVICIAN AREA, ARKANSAS

BY A. H. PURDUE

[*Abstract*]

The area herein considered lies in the western central part of Arkansas. It is one of two Ordovician areas within the state, the other occurring in the northern part and being the southern extension of the Cambro-Ordovician area of Missouri. Between the two areas there is a large structural trough occupied by rocks of Lower and Upper Carboniferous age, and containing the Arkansas valley.

The area is mountainous and is occupied by parallel east-west ridges. These ridges have steep, rocky slopes and inclose narrow valleys. Many of them reach from 1,800 to 2,000 feet above sea-level, or from 800 to 1,000 feet above stream level. Through them occur numerous water-gaps formed by the southward flowing streams.

The general structure is that of an anticline with an east-west axis. This

is spoken of in the geological reports of Arkansas as the Ouachita anticline. On either limb of the anticline the structure is exceedingly complicated, consisting of minor symmetrical anticlines, and overturned, closely compressed anticlines and synclines. Thrust faulting is common, parallel with the folds. Scarcely two of the ridges have the same structure, and that of any ridge is liable to change within short distances.

The rocks of the area are sandstone, shale, some limestone, chert, and novaculite. At least eight different formations are recognized. These are here tentatively named, beginning with the lowest, Collier shale, Crystal Mountain sandstone, Caddo shale, Big Fork chert, Polk Creek shale, Blaylock sandstone, Slatington shale, and Missouri Mountain formation (novaculite, sandstone, and shale).

The rocks of the area have been determined by the geological survey of Arkansas as of Ordivician age, from the graptolites that occur profusely at two horizons. There is apparently a marked unconformity at the top of the Blaylock sandstone. As the graptolite horizons noted by the present writer are below this, the possibility of the Slatington shale and the Missouri formation being of Silurian age presents itself. These formations have so far proved unproductive of fossils.

This paper was discussed by A. C. Lane and G. K. Gilbert.

Soon after 5 o'clock the Society adjourned, and at 7.30 met again in the dining-room of the Hotel Alvarado for its annual dinner, which was enjoyed by thirty-seven persons, including a few of the prominent educators of the territory.

Session of Tuesday, December 31, 1907.

The Society convened at 9.10 a. m., with President Van Hise in the chair. The report of a committee favoring the establishment of a series of stations for the study of volcanic and seismic phenomena was adopted. The consideration of an overture on the formation of a Committee on Geological Nomenclature was deferred to the end of the session. The report of the Council was accepted and ordered printed in the Proceedings, and the auditing committee was continued and given leave to report to the Council after the adjournment of the Society. The Society then proceeded with the reading of papers, the first two being presented together by Professor J. E. Wolff. They were

NOTES ON THE CRAZY MOUNTAINS, MONTANA

BY JOHN E. WOLFF

[*Abstract*]

The Crazy mountains were visited by the author in 1883 and 1889, and a paper on their geology was published in the Proceedings in 1892. Last sum-

mer, with Dr G. R. Mansfield and Mr H. E. Merwin, a review was made of their physiographic and geologic features, and some three hundred photographs were obtained, dealing with points of especial interest. One small glacier was discovered and visited, and another, not so readily accessible, was noted; the relative age of the granite-diorite stocks and of alkali-syenite was found and minor points determined. After a review of the geology of the mountains and of their special features, the results of last summer's work were described and the whole illustrated by a small selection of lantern slides. The accompanying paper, by Doctor Mansfield, was included in Professor Wolff's presentation:

GLACIATION IN THE CRAZY MOUNTAINS OF MONTANA[1]

BY GEORGE ROGERS MANSFIELD

Contents

Introduction

The Crazy mountains (figure 1) occupy a somewhat oval area in central Montana, about 40 miles long from north to south, and 15 to 20 miles wide. The middle portion is approximately 46 degrees 10 minutes north latitude and 110 degrees 20 minutes west longitude. The mountains are divided by the broad basin of the Shields river into two practically separate sections—the north and the south—although there is a narrow connecting ridge along the east side. The two areas thus determined constitute distinct units, both topographically and geologically, and each has an approximately radial system of drainage. The northern section rises to a maximum altitude of about 9,200 feet, and is marked by gentle outlines in its upper slopes. The southern section, which occupies a larger territory, reaches a maximum height of 11,178 feet above the sea, and is very rugged.

In the summer of 1907 the writer, in conjunction with Professor J. E. Wolff, conducted a geological field party from the Harvard Summer School through these mountains. After the close of the school he assisted Professor Wolff in

[1] Introduced by John E. Wolff.

Contour Interval 200 feet
Datum is mean Sea level

Figure 1.—*Map of a Portion of the Crazy Mountains Area.*

From the Little Belt and Livingston quadrangles of the U. S. Geological Survey.

the latter's study and revision of the geology of the region, the completion of investigations begun some years earlier. Mr H. E. Merwin also accompanied Professor Wolff as assistant, and was associated with the writer in much of the latter's work on the glacial features of the mountains.

Previous accounts of the Crazy mountains have given little attention to the glaciation of the region. A brief general statement is made in one of Professor Wolff's papers,[1] and mention of glacial action is made in the Livingston and Little Belt Folios, United States Geological Survey, by Messrs Iddings, Weed, and Pirsson, who mapped some of the glacial deposits. Mr J. H. Ropes, who accompanied Professor Wolff on one of his earlier expeditions, studied the effects of glaciation in these mountains, but his unpublished report is not now available.

In the expedition of 1907, members of the party visited each of the main canyons and many of the smaller ones. Some of the larger branches of the main canyons were followed to their very heads, and studied in detail, but others were observed more distantly, from ridges or peaks that afforded good views into the heads of the major and minor canyons.

Character of Glaciation

The continental ice-sheets, which invaded northern Montana, did not extend to the Crazy mountains. The terminal moraine, according to recent studies,[2] passes near Great falls and along the north side of the Highwood mountains 60 or 80 miles to the north, and stretches away eastward 50 or 60 miles north of the latitude of the Crazy mountains to the border of the state. These mountains were, however, locally glaciated and contain numerous examples of the cliff and valley types, and even two or three piedmont glaciers.

Number and Dimensions of Glaciers

All the valleys that head well up in the mountains formerly supported glaciers, large or small. In many cases these were comparable in size to the Swiss glaciers of today. The largest were on the south and east sides of the mountains. Cottonwood (Pine) creek[3] on the southwest and Big Timber, Sweetgrass, American Fork, and Big Elk creeks on the southeast and east must have had glaciers approximating 10 to 18 miles in length, as indicated by the position of morainic deposits.

The glaciers of Sweetgrass and American Fork creeks on the east side of the mountains apparently combined to form a piedmont glacier that had an irregularly oval outline, approximately 7 or 8 miles in length from northwest to southeast, and 3 or 4 miles in width, according to the morainic deposits mapped by Messrs Weed and Pirsson.[4] There seems to have been also a smaller piedmont glacier produced by glaciers from the south fork of Big Tim-

[1] The Geology of the Crazy mountains, Montana. Bulletin of the Geological Society of America, vol. 3, 1892, pp. 445-452.

[2] F. H. H. Calhoun: The Montana lobe of the Keewatin ice-sheet. Professional Paper no. 50, U. S. Geological Survey, 1906.

[3] Names in parentheses are those given on the topographic map, when the latter differ from those locally used.

[4] Little Belt folio, U. S. Geological Survey.

FIGURE 1.—GLACIER AT THE HEAD OF BIG TIMBER CREEK

Photograph by H. E. Merwin

FIGURE 2.—CIRQUE AND LAKELET AT THE HEAD OF SWAMP CREEK

GLACIAL PHENOMENA IN THE CRAZY MOUNTAINS

ber creek and Swamp creek, for moraines from these canyons overspread their valley sides and combine. Possibly the north fork of Big Timber may have contributed to this piedmont sheet, but the region between the two forks of Big Timber was not studied.

In his previous report on the Crazy mountains Professor Wolff estimates the elevation of striæ as 500 or even 1,000 feet above the present stream beds.[5] The observations of the present writer confirm that estimate. The elevation of striæ, the height of cliffed slopes along the edges of glacial troughs, and the altitude at which side troughs now hang above the main trough floors go to show that the main glaciers must have had a thickness of between 500 and 1,000 feet.

Living Glaciers

Glaciation in the Crazy mountains is not yet extinct. At the head of the west branch of the north fork of Big Timber creek, facing to the northeast, there is a small cliff glacier at an altitude of 9,000 to 9,500 feet. The length of the glacier, including its snow field, is probably not more than an eighth of a mile, while its width is about one-fourth of a mile, giving an area of about 20 acres. This glacierlet was discovered by the Harvard Summer School party on July 31, 1907. The failure of previous observers to note its true character was doubtless due to the fact that it is generally covered with light snow that effectually conceals its structure. The general features of the glacier are shown in plate 35, figure 1. In the midst of what appears to be an ordinary snow patch is seen a mass of dirty ice, showing distinct banding and contortion with shearing. Miniature crevasses, extending obliquely backward from near the east side, show the characteristic greenish blue color of glacier ice. The morainic material seen in the foreground of plate 35, figure 1, lies at least in part upon dirty, banded ice. The convex front of the ice changes gradually into the concave surface of the snow field, and, at the back of the latter, cracks in several places indicate the presence of the bergschrund. The walls of the enclosing cirque rise sheer 500 to 700 feet to the ridges and peaks above. The melting snow and ice drains into a lakelet on the floor of the trough below. A recent letter from Mr E. C. Russell, forest supervisor at Livingston, Montana, states that in September of this year large blocks of ice, that had broken off the glacier, had fallen into this lakelet.

Near the head of the south branch of the south fork of Sweetgrass canyon, where it heads against the east fork of Cottonwood (Pine) creek, there is a large snowfield that is believed by the writer to conceal another small glacier. This snowfield lies at an altitude of nearly 10,000 feet and faces northeast. It was not visited by the party, but, seen from a distance, it presents the same convexo-concave slope noted in the case of Big Timber glacier. Several cracks were observed at the head of the snowfield, and an obscure oblique structure running downward from west to east was noted in the snow, as if the latter only partly concealed banded ice. No other snow patches seen displayed such characteristics, save only that containing the Big Timber glacier.

A third glacierlet in the head of Rock creek is reported by Forest Assistant R. B. Wilson in an unpublished manuscript. He does not specify the position of this glacier except by general reference. The creek has two well defined

[5] Op. cit., p. 446.

branches, the north and the east. It is probable that the latter contains the glacier, for Professor Wolff and Mr Merwin, who examined the north branch, found no evidence of it in that canyon. The east branch was not visited by the party.

Effects of Glaciation

Cirques and Hanging Valleys

All the higher valleys in both sections of the mountains have cirques at their heads. The steep or precipitous walls are usually well marked, but often later accumulations of slide rock have modified to some extent the earlier outlines. In the northern section of the mountains cirques occur mainly in the region of Loco mountain, the highest summit, where they cut sharply into the gentle, ancient topography of the mountain. In the southern section cirques occur throughout the area above the foothills, and, where adjacent cirques worked backward on opposite sides of divides, sharp arrêtes have been produced. Two-story cirques occur in a number of places, fine examples having been observed near the supposed glacier in Sweetgrass canyon and in the north fork of Rock creek. Plate 35, figure 2, shows a beautiful cirque, with lakelet at the head of the north branch of the south fork of Swamp creek.

Hanging valleys may be seen on the sides of the larger canyons. Good examples occur in the canyons of Big Timber, Sweetgrass, and Rock creeks. Plates 36 and 37, figure 1, show hanging valleys in Rock canyon and Big Timber canyon respectively. In each case the upper valley hangs at least 600 feet above the main trough floor. In plate 37, figure 1, the hanging valley on the south side (left of picture) consists really of at least four shallow troughs, each separated from its neighbor by a low rock ridge, and each representing the outflow from a separate cirque. Near the rim these subordinate troughs unite, and send their drainage out through a branching stream that leaps in a double series of small cascades to the floor of the main valley below. Two other subordinate notches occur in the rim, but these contain no streams. Apparently the combined output of ice from the several cirques was insufficient in quantity, and worked for too brief a time to efface the low boundary ridges of the minor troughs, so that, while the surfaces of the contributing ice streams doubtless joined, the streams themselves were enabled to maintain their individuality almost to the very rim.

Troughs

The lower canyons have broad, flaring, trough-like cross-sections, and the trough constitutes nearly all, or, indeed, the entire valley (see plate 37, figure 2). In the upper canyons, where the hard rocky core of the high mountains is penetrated, the troughs form a much smaller proportion of the valleys, and the latter appear rather broadly V-shaped. In plate 37, figure 1, the main valley of Big Timber creek is seen to have long slopes of normal erosion above the top of the glacial trough. This relation seems to hold throughout the higher parts of the mountains. The valleys are in the main rather straight, and the spurs that would normally enter from the side have been cut back. This truncation is not, however, limited to the slopes included within the troughs, but extends as well to the upper slopes that have not been glaciated. Thus the glacial troughs seem to have been formed in valleys that had already

HANGING VALLEY OF EAST FORK OF ROCK CREEK, MONTANA

Photograph by H. E. Merwin

FIGURE 1.—NORTH FORK OF BIG TIMBER CANYON

View looking west from a point 5 or 6 miles east of the head and showing hanging valley and glacial trough. Photograph by J. E. Wolff

FIGURE 2.—BIG TIMBER CANYON

View eastward from a point 3 miles below the head, showing trough-like lower canyon

GLACIAL PHENOMENA IN THE CRAZY MOUNTAINS

been broadly opened and straightened by normal erosion, so that ice action has not greatly modified them.

STRIÆ AND DEPTH OF CUTTING

Striæ are found only in the upper parts of the larger canyons, in the region of the hard rocks of the igneous cores and contact zones of the mountains. Elsewhere the rocks have weathered sufficiently to remove or conceal the ice markings. Even in the region where the rocks are hard, slide rock and morainic material mask the glaciated surfaces so that actual striations are not frequently seen. Well developed roches moutonées were, however, studied in Big Timber and Sweetgrass canyons and more distantly observed in other canyons. The directions of all striæ seen agreed with the general trends of the valleys in which they were found. The presence of striæ indicates that the original valleys have been deepened by the ice to some extent at least. Outside the hard rock area the canyons have doubtless been more deeply eroded, and then partly filled with glacial and fluviatile material. The general depth of the filling is not known, since most of the streams have not yet succeeded in cutting through it. In Cottonwood (Pine) canyon, however, about 3 miles below the junction of the north and east forks, the stream has reached bedrock through 10 to 15 feet of till, which thins out down stream and grades into water-worn material.

MORAINES AND WASH DEPOSITS

Moraines are found in the lower parts of the larger canyons, but are usually not well defined toward their heads. Accumulations of slide rock, which occur almost everywhere, have mingled with and obscured the morainic materials of the upper valleys. Some moraines occur on the western side of the mountains, on the benches sloping northwestward to the Shields River basin, but the heaviest deposits are those previously mentioned in connection with the ancient piedmont glaciers on the east side. Small lateral moraines occur in some of the canyons. The best examples were seen at the heads of Sweetgrass and American Fork creeks. In many of the cirques little moraine-like humps of slide rock have accumulated about the base of the back and side slopes, as if loose pieces of rock had fallen on the surfaces of the snow patches that occupy the cirques, and had been deposited in irregular heaps when the snow melted away.

Within the area visited by the party there was very little fluvio-glacial material. Doubtless most of such debris had been deposited farther down in the valleys. In one place, however, a fine section of stratified sands and clays was found, namely, in the valley of the east fork of Duck (Gage) creek, about 5 miles south-southwest of Fairview peak.

LAKELETS

Numerous lakelets occupy rock basins in the cirques and higher valleys. They are seldom more than 200 or 300 yards in diameter. Sometimes they occur in strings of three or four. They are mostly found in the canyons of streams that flow eastward and southeastward from the mountains, though a few are found in some of the west-flowing creeks. From the summit of Crazy peak one of the members of the party counted 18 of these lakelets, several of

them partly or wholly ice-covered. One of the most beautiful examples is shown in plate 35, figure 2.

Other lakelets or moist hollows occur among the morainic deposits in the lower canyons or on the foot slopes of the mountains, particularly in the vicinity of Sweetgrass and American Fork creeks. A steep-sided lake of this kind near Swamp creek was estimated to be one-fourth of a mile in length.

The largest lake in the Crazy mountains, known as Cottonwood (Forest) lake, in the northern section, owes its being to an obstruction of loose porphyritic blocks, that is probably morainic, though other signs of glaciation in the valley in which it occurs are not very distinct. The linear form and fairly regular outline of the lake are favorable to this view, though the valley is not very trough-like in character, has no cirques at its head or along its sides, and has no other well defined morainic deposits.

The alternative view that the obstruction is simply a pile of fragments of a hard dike or sheet weathered *in situ* is not supported by evidence of the continuation of such dike or sheet on the sides of the valley. The porphyritic masses appear to be all of the same kind, but might have come from similar rocks up valley.

Relations to Previous Topography

Peneplanation

Reference has been made to the gentle outlines of the upper topography of the northern section of the mountains. Loco mountain, the main *massif* of that region, has a nearly flat top 3 or 4 miles long and 1 or 2 miles wide at an altitude of 9,000 feet. A small knoll rising 200 feet above the general level forms Loco peak, the highest summit. The gentle outlines here mentioned have been produced upon both sedimentary and igneous rocks, regardless of structure, and represent an ancient surface of erosion. This is now deeply cut by the later cirques and canyons, but down the main divides one may follow the older topography with moderate grade to the gentle foot slopes, remnants of which now form the beautiful benches that slope away from the mountains at an angle of about 5 degrees, 100 feet or more above the present stream valleys.

In the southern section the altitudes are greater and the general topography more rugged, but many of the ridges rise to fairly accordant levels, and here and there small remnants of a flat surface occur at an altitude of about 10,000 feet. The main divides descend to gently sloping benches as in the northern section. The truncation of widely different rocks and structures by the older topography of mountain and bench land shows that the region was formerly subjected to extended erosion, sufficient to produce an early stage of peneplanation. The superior hardness of the central cores of the mountains permitted the latter to retain subdued mountainous relief, for the summits now lie 3,000 to 4,000 feet above the upper limits of the benches.

Revival

After peneplanation the region was revived. Two well defined sets of rock benches, lower than the ones already described, show that there were at least two periods of erosion before the present one. The earlier of these appears

to have reached a late mature stage, while the later one was somewhat less advanced. The present deep canyons were probably excavated and broadened and the lateral spurs cut back during these periods of erosion. The evidence of these two later cycles is less well marked within the mountains than in the bench land outside. In Sweetgrass canyon, however, just inside the contact zone, the rocks are very hard and the canyon boxes. The walls at this point are divided into four minor slopes, with noticeable breaks in grade between successive portions. The uppermost set of slopes indicates a relatively broad and open valley with gently sloping concave sides. The two next lower sets are smóothed and somewhat concaved. The lowest slopes descend steeply to the present stream bed. The uppermost set of the slopes here indicated appears to represent an earlier, broadly opened valley of the ancient topography, while the three lower sets represent respectively the two later erosion stages and the present cycle. The trough-like appearance of the head of Big Timber canyon (plate 37, figure 1) is very likely due merely to glacial modification of the valley of the second of the later cycles, while the upper slopes represent the first, the more ancient topography having been obliterated in that region.

ALTERNATIVE HYPOTHESES

The alternative hypothesis, that the benches and slopes mentioned do not represent revival, but merely differential erosion in rocks of varying hardness, does not find support in the case of the Sweetgrass locality just cited, for the slopes are cut in hard igneous rocks that have practically uniform vertical distribution. The benches, too, are very distinct in many localities rather widely separated, and differing in geological horizon and structure, yet they seem to maintain fairly constant relations to each other.

The hypothesis that the benches are merely alluvial terraces is not supported by the facts. The benches are only thinly covered by gravels. Near their tops exposures of bed rock occur in the later ravines. The forms in question are true rock benches due to revival by uplift, which must have been sufficiently extended to include the area observed.

ADVENT OF ICE

Morainic material lies on the uppermost benches, and also at lower levels within the lower cånyons, but in the latter case it is not certain whether the glacial deposits rest on rock benches or simply represent morainic fillings. In the Sweetgrass gateway above described, however, the two intermediate sets of slopes have been glaciated, while the lowest is not striated and appears to be post-Glacial. Hence it seems probable that occupation by ice succeeded the second of the later cycles of erosion.

DURATION OF GLACIATION

It has been shown that in the lower canyons the trough form includes nearly or quite the entire valley, and that in the bench lands the ice at times even overspread the valley walls. In the upper canyons, however, the troughs form much less conspicuous parts of the valleys. Slopes of normal erosion extend 2,000 to 3,000 feet above the tops of the troughs. Though the divides are generally sharp, they are more frequently the product of normal erosion than of

the development of cirques. When due to the latter cause the opposing slopes of the divide become precipitous and sharp arrêtes are formed.

The hanging valleys in Big Timber canyon and elsewhere indicate a considerable amount of glacial erosion, at least locally, but the relatively narrow gateway in Sweetgrass canyon does not show much modification by ice action. The rocks both within and without the contact zone of the sediments with the eruptives are weaker than those of that zone, so that the canyons broaden both above and below that region. The contact zone would thus mark a belt of minimum deepening, which at the time of occupation by glaciers was probably the site of ice falls, as it now is of cascades. Above this zone the maximum deepening, as indicated by the hanging valley in Big Timber, may have been as much as 300 or even 500 feet. Below this zone the maximum deepening may have equalled or even exceeded that figure; the streams have not yet penetrated the glacial filling. But the additional depth of 300 or 500 feet produced by glacial action in a canyon where the sides rise 2,000 or 3,000 feet above the valley floor, cannot be regarded as a very extensive modification of pre-Glacial form.

The topographic features of the Crazy mountains thus seem to be mainly pre-Glacial. The ice remained long enough to deepen and modify the form of existing valleys and to develop the cirques and arrêtes so common in the higher mountains.

Post-glacial Erosion

At the heads of the canyons the streams are cutting new gorges for themselves beneath the old trough floors. These are still so immature that the rims of the hanging valleys are barely notched by them as they leap in cascades to the valley floors below. The glacial lakelets are for the most part unfilled and undrained. In the north branches of the east fork of Cottonwood (Pine) creek, sharply cut V-shaped gorges were observed in the fillings of the glacial valleys, but these gorges had not penetrated the filling, which was 100 feet or more in thickness, and had not reached grade. In the hard rocks of the contact zone, cascades have developed and some incision has been accomplished, while in glacial fillings below this "fall line" the streams have reached grade, without cutting through the filling, and rush along through stony flood plains. In the lower canyons of some of the larger creeks, such as Cottonwood (Pine) and Sweetgrass, the streams have cut into the bed rock and developed gorges 100 feet or more in depth. In Sweetgrass creek a beautiful meander belt has been established, for a distance of about 3 miles, in the weak rocks near the lower end of the canyon.

Within the area affected by the glaciers post-Glacial erosion has accomplished little in the way of readjustment of drainage. Indeed, the drainage may be said to be highly immature. Outside the glaciated area, however, erosion has progressed steadily from the glacial time to the present. The larger streams have developed broad flood plains, such as those of the Shields river and the Yellowstone, and many of the smaller ones have reached grade.

Summary

During the Glacial period the Crazy mountains were the seat of local glaciation. Cliff, valley, and piedmont glaciers were formed, the largest being on

the southeast and east sides of the mountains, where some attained a length of 10 to 18 miles and a thickness of 500 to 1,000 feet. Glaciation is not extinct. A small cliff glacier occurs at the head of Big Timber canyon and another in Sweetgrass, while a third is reported at the head of Rock creek. Previous to glaciation the region had reached an early stage of peneplanation and had been revived in two partial cycles of erosion. Glaciation did not continue long enough greatly to modify pre-existing topography, but did produce broad, deep troughs in the weaker rocks and arrêtes in many of the sharp divides. Later stream erosion has incised the glacial deposits and, in some cases, the old trough floors.

The papers were discussed by A. C. Lawson.

The following papers were read by title:

SHALER MOUNTAINS, UNALASKA, A GRANITE CORE TO THE ALEUTIAN ISLANDS

BY T. A. JAGGAR, JR.

GROWTH AND DESTRUCTION OF METCALF CONE, BOGOSLOFF ISLAND, 1906-7

BY T. A. JAGGAR, JR.

Then was read

SANDIA MOUNTAINS

BY W. G. TIGHT

The following papers were then read by title:

GEOLOGY OF THE ALASKA RANGE

BY A. H. BROOKS

PALEOZOIC AND ASSOCIATED ROCKS OF THE UPPER YUKON BASIN

BY A. H. BROOKS AND E. M. KINDLE

GEOLOGIC RECONNAISSANCE OF THE PORCUPINE VALLEY, ALASKA

BY E. M. KINDLE

The last two papers were published as pages 255-338 of this volume.

The following paper was read by title:

DISCOVERY OF FISH REMAINS IN ORDOVICIAN OF THE BLACK HILLS, SOUTH DAKOTA

BY N. H. DARTON[1]

[Abstract]

Two years ago I announced to this Society the discovery of fish remains in the Ordovician (Bighorn formation) of the Bighorn mountains, and gave a résumé of our knowledge of the Ordovician of the Northwest.[2] During the

[1] Published by permission of the Director of the U. S. Geological Survey.
[2] Bulletin of the Geological Society of America, vol. 17, pp. 541-566, plates 73-79.

past summer I had occasion to extend my examination of the Ordovician of the Black Hills in South Dakota, and at one locality 15 miles northwest of Rapid I discovered fish remains similar to those previously reported from the Bighorn mountains and by Mr Walcott[8] in the region west of Canyon City, Colorado. The remains were submitted to Mr Walcott, and now await his report as to genera and species. Unfortunately it was practicable to obtain only a small mass of the fossil-bearing rock, but its stratigraphic position was evident. The precise locality was one mile north-northeast of Nemo post office, a small settlement on a branch railroad about half way between Deadwood and Rapid. It is on the northeastern slope of the general Black Hills uplift, where the rocks dip to the northeast at a low angle.

The Ordovician in the Black hills is represented by a formation which has been designated the Whitewood limestone from typical exposures on Whitewood creek about 2 miles below Deadwood. The rock is hard, massive, somewhat siliceous, and ordinarily of buff color with brownish spots or mottlings. It contains large endoceras, maclureas, and corals of Trenton age. Its thickness is 80 feet near Deadwood, but it thins rapidly to the south, and it is entirely absent in the latitude of Rapid. The location of the southern margin was not ascertained precisely, owing to talus which covers the slopes, but the limit of the main outcrop is several miles north of Nemo. The limestone lies unconformably on Deadwood formation (Middle Cambrian), and is overlain by the Englewood limestone of the Mississippian division of the Carboniferous. Above and below it are thin bodies of green shales which yield no fossils, but are included in the overlying and underlying formations. The lower shale, and possibly also the upper one, extends south beyond the margin of the Whitewood limestone, usually constituting a slope between a bench of the upper sandstone of the Deadwood and a cliff of the lowest limestone of the Carboniferous. It was on a slope of this character, northeast of Nemo, that I obtained the limestone fragment containing the fish remains. It probably represents a very thin outlier of the Whitewood limestone lying on the green shale which here is regarded as the top member of the Deadwood formation.

The next paper read was

TOPAZ-BEARING RHYOLITE OF THE THOMAS RANGE, UTAH

BY HORACE B. PATTON

The paper has been published as pages 177-192 of this volume.

The paper was discussed by G. K. Gilbert.

The next two papers were read without break.

STRATA CONTAINING THE JURASSIC FLORA OF OREGON

BY J. S. DILLER

LOCAL SILICIFICATION OF THE KNOXVILLE

BY J. S. DILLER

[8] Bulletin of the Geological Society of America, vol. 3, pp. 153-167.

The first of the two papers was published as pages 367-402 of this volume.

The second paper was discussed by A. C. Lawson.

On account of the special interest due to the excursion after the meeting to the Grand Canyon of the Colorado, the following paper was, in the absence of its author, read by C. W. Hayes:

WIND EROSION IN THE PLATEAU COUNTRY

BY WHITMAN CROSS

This paper has been published as pages 53-62 of this volume.

The next paper was read by title:

ASSOCIATION OF PEGMATITE WITH HORNBLENDIC BORDER BEDS OF GRANITE AND THE APPEARANCE OF LARGE ISOLATED MASSES OF THE TWO TOGETHER DEEP IN THE GROUND

BY B. K. EMERSON

The next paper was read by Mr. Louderback. It was

BENITOITE: ITS MINERALOGY, PARAGENESIS, AND GEOLOGICAL OCCURRENCE

BY GEORGE D. LOUDERBACK AND W. C. BLASDALE

[*Abstract*]

Benitoite and the associated minerals were briefly described and chemical analyses presented. The paragenesis and geological mode of occurrence were discussed and compared with geologically related but mineralogically different deposits in the same geologic province.

The paper was discussed by W. G. Tight.

The next papers were read by title, as follows:

IGNEOUS ROCKS OF THE ORTIZ MOUNTAINS

BY IDA H. OGILVIE

PRE-GLACIAL DRAINAGE IN CENTRAL WESTERN NEW YORK

BY AMADEUS W. GRABAU

The next paper was read by title. It was

GEOLOGIC PROCESSES AND GEOGRAPHIC PRODUCTS OF THE ARID REGION

BY CHARLES R. KEYES

[*Abstract*]

Contents

INTRODUCTORY

The Albuquerque meeting of the Geological Society is in its history the first, I believe, ever held under conditions of an arid climate. Under such circumstances attention is appropriately directed to certain features of the landscape about and to some of the peculiarities of the geologic operations producing them. In the normal humid climate some of these relief features would be ascribed to very different causes. Under conditions of aridity the geologic agencies at work modifying the facial expression of our globe operate in a manner so very different from what they do in a humid land that the effects can only be fully appreciated after long residence in a dry country.

It is a remarkable fact that the arid regions have given us our two most comprehensive and important generalizations regarding the evolution of the geographic features of our earth. The first of these is, of course, the theory of the base-level of erosion, as first propounded by Powell, after his extensive explorations of the Great Basin region of western America. The second is the hypothesis of the complete leveling of elevated continental areas without base-leveling, as urged by Passarge, for the great interior plateau of South Africa. One principle develops the geographic cycle under conditions of normal humidity; the other, not less significant, is the foundation for the recognition of a distinct geographic cycle in a dry climate.

FIGURE 1.—PLAINS OF THE JORNADA DEL MUERTO, NEW MEXICO

Worn out on beveled strata; distance to rim, 30 miles

FIGURE 2.—FRANKLIN MOUNTAINS, NORTH OF EL PASO

The tilted limestone layers of the Backslope are seen even at a distance of 10 miles, as in this view

DEFLATIVE EFFECTS IN THE DESERT

Relation of New Mexico to adjacent Arid Regions

All of New Mexico is commonly regarded as forming a part of the Southwest desert. It is, however, peculiarly situated in that it lies at the meeting point of four great physiographic provinces of our continent. Their boundaries in New Mexico are outlined in the accompanying sketch-map (figure 1). These provinces are the Great plains, occupying the eastern part of the territory east of the Pecos river; (2) the Rocky mountains, reaching southward

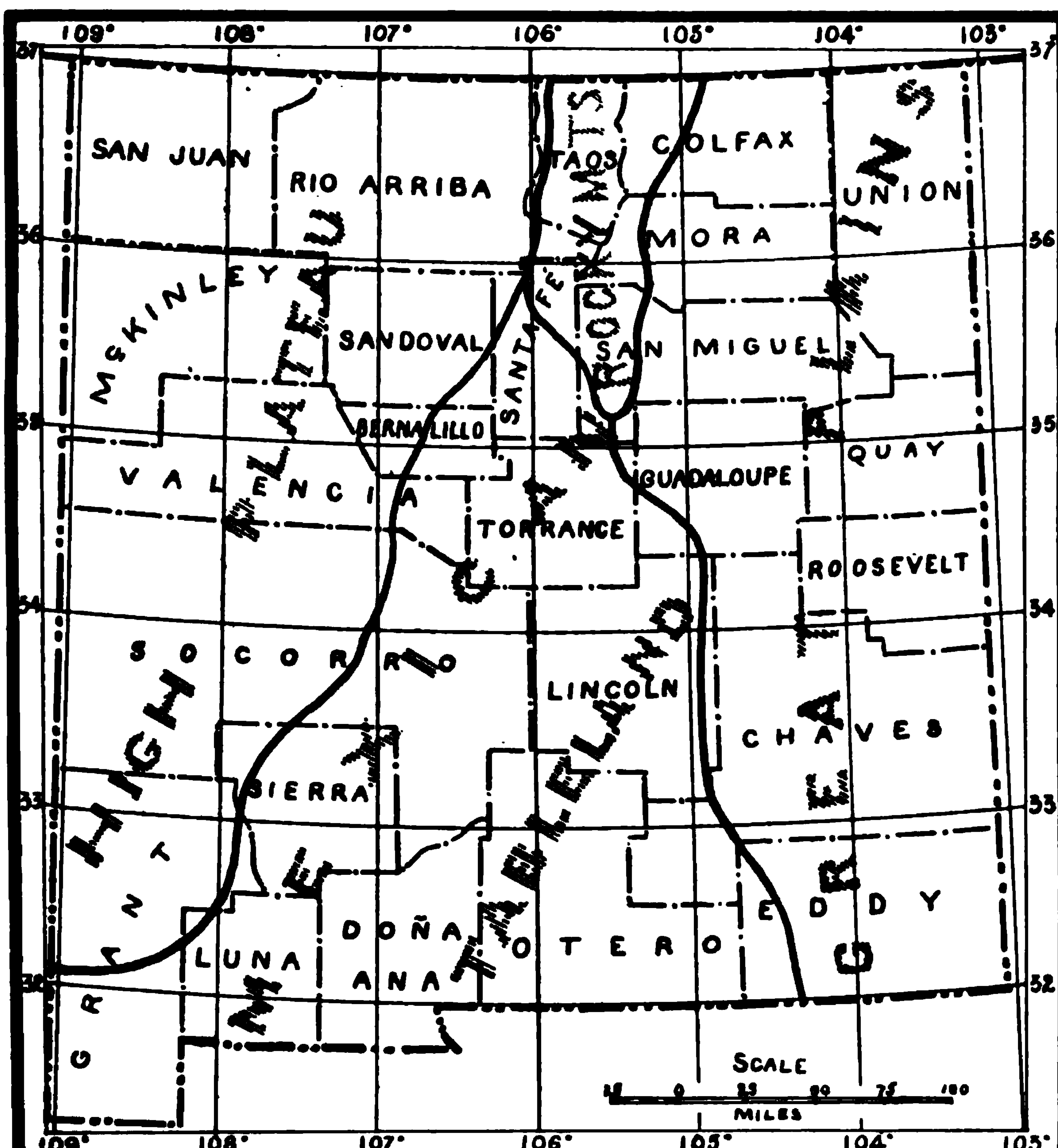

Figure 1.—*Sketch Map of New Mexico, showing Physiographic Provinces*

from Colorado in a long narrow tongue to the Glorietta pass; (3) the Mexican tableland, in the south-central part; and (4) the High Plateau province, including all of the northwest.

These four geographic provinces as represented in New Mexico differ so widely from one another in general surface relief, geologic formation, geotectonic arrangement, drainage features, climatic conditions, soil character, plant growth, economic resources, and harmonious environment for human habita-

tion that the passage from one to another is very soon noted. In the present connection it is to be remembered that of the four provinces only the Mexican tableland and the High, or Colorado, plateau have typically arid climates; the Great Plains province represents semi-arid conditions; while the Rocky Mountains province possesses a semi-humid or humid climate.

The special workings of the geological processes to which attention is soon directed are the extent, rapidity, and vigor with which eolian erosion or deflation goes on, the feebleness and infrequency of normal water-action, and the remarkable effects of sheetflood transportation.

In the light of a distinct geographic cycle for an arid climate recently recognized, some of the most striking peculiarities of the region about us must be viewed quite differently from what they were before. Brief allusion is here made to some of the most important and also to some of the best local examples. The real significance of the commonest features now possess a new interest and their origin a new interpretation.

It may be noted in passing that the Rio Grande valley does not exhibit most of these features in typical form, for the reason that this stream is not a characteristic desert drainage-way, but a great river snow-fed and flowing through to the sea. Although it receives no perennial tributaries for a distance of a thousand miles it is a typical humid-land stream, with high gradient and great corrading powers. The old original plains-level, or bolson surface, over which it once flowed, is 500 to 1,000 feet above the present channel. Throughout its entire course of 300 miles in New Mexico it receives only sporadic and torrential waters from the lofty mountains on either side. Nevertheless, in the neighborhood of Albuquerque illustrations of all of the phenomena mentioned are well displayed, and especial attention may appropriately be called thereto.

Characteristic geographic Features

Vastness and evenness of intermont plains

Such plains as the Estancia plains, the Hueco bolson, and the Jornada del Muerto appear to owe their leading characteristics directly to the plains-forming effects of wind-action; and to be the immediate product of local desert-leveling without base-leveling. The last mentioned plain is, perhaps, as typical as any that could be named. The view (plate 38, figure 1) shows an expanse of 30 miles in front of the highland rim in the background; the length of the plain is over 200 miles.[1]

Isolation of the mountains

Ortiz laccolith, the Magdalena block, Sandia range, and Socorro volcano are examples. It is to be noted that this isolation is perfectly independent of mountain origin. With few exceptions, the mountains rise monadnock-like out of the even plains. The lofty and steep-sided Ortiz, Tuertos, and San Ysidro groups, to the east of Albuquerque, are separated only by five or six miles of flat valley-plains, yet preserve their characteristic isolation.[2] The Franklin block, north of El Paso, finely displays this same characteristic (plate 38, figure 2).

[1] U. S. Geological Survey, Water Survey and Irrigation Paper no. 123, 1905.

[2] Journal of Geology, vol. xvi, 1908, pp. 434-451.

FIGURE 1.—SIERRA OSCURA, IN CENTRAL NEW MEXICO

Range rises isle-like out of sea of earth; distance, 15 miles; height, 3,000 feet

FIGURE 2.—SOCORO MOUNTAIN, NEW MEXICO

Height, 2,000 feet

ABSENCE OF FOOTHILLS IN DESERT RANGES

FIGURE 1.—COYOTE RANGE, SOUTHERN ARIZONA

Characteristic sharp meeting of mountain and plain

FIGURE 2.—CRETACIC SANDSTONES NEAR LOS CERRILLOS, NEW MEXICO

Plain beveling tilted strata

TWO DESTRUCTIVE DESERT FEATURES

COMPLETE ENCIRCLEMENT OF MOUNTAINS BY PLAINS

The mountains everywhere rise abruptly out of the plains, as do volcanic isles out of the sea. The Jemez, Florida, Caballos, and Oscura ranges, which finely display this feature, are only typical of the large majority of the mountains of the southwest.[3] The view of the last mentioned range is from a point on the Jornada del Muerto, 15 miles distant (plate 39, figure 1).

CHARACTERISTIC ABSENCE OF FOOTHILLS

This is one of the most surprising features of the arid region. One leaves plain and plunges by way of deep canyon at once into heart of mountain. There are no foothills about the Sandias. The Tijeras is a narrow and profound canyon until it meets the plain.[4] The Socorro mountain well illustrates this feature (plate 39, figure 2). A still more characteristic view, shown in plate 40, figure 1, is from a photograph by W J McGee of the Coyote range of southern Arizona, rising over 3,000 feet above the plain.

RESISTANT CHARACTER OF MOUNTAIN ROCKS

Independent of the origin and original rock-makeup of the mountains it is significant that it is the most resistant rocks which form them. The Sandia block is chiefly ancient crystallines and hard Carbonic limestones; the Ortiz group is mainly mica-andesite, which was originally covered by great thicknesses of Cretacic sandstones; Socorro mountain is made up of Tertiary lava flows. All of these mountains are essentially arid monadnocks rising above the plains.

SOFT SUBSTRUCTURE OF THE PLAINS

The Las Vegas plains are worn out on the soft Colorado shales; the Estancia plains have a substructure of friable Cretacic sandstones and shales; the old bolsons of the present Rio Grande valley above and below Albuquerque are floored by Early Tertiary deposits.

BEVELED ROCK-STRUCTURE OF PLAINS

In the valley of the Rio Galisteo, north and east of Albuquerque, and near the town of Los Cerrillos, the plains-surface is clearly shown in the field to bevel the rock-structure (plate 40, figure 2). The Jornada also displays the same phenomenon,[5] as does the Chupadera mesa to the east of the Jornada. The Rio Grande valley near Socorro gives many evidences of the old beveled rock-floor.

PLAINS CHARACTER OF THE ROCK-FLOOR ITSELF

In the valleys of La Jara and Arroyo San Pedro, east of the Sandia range, the surface of the rock-floor is exposed for distances of many miles. Everywhere the rock-floor is seen to be an even surface independent of the surface deposits.[6]

[3] Journal of Geology, vol. xiii, 1905, pp. 63-70.
[4] Bulletin of the Geological Society of America, vol. 12, 1901, pp. 217-270.
[5] U. S. Geological Survey, Water Supply and Irrigation Paper no. 123, 1905.
[6] Engineering and Mining Journal, vol. lxviii, 1904, pp. 670-671.

REPRESENTATION OF FORMER PLAINS-LEVELS BY THE PLATEAU PLAINS

Mesas, or plateau plains, are one of the most characteristic features of the New Mexican arid region, and they are usually due to protective caps of old lavas which flowed out on the plains when the latter were at a higher level than at the present time. For the most part they may be, therefore, regarded as representing former levels of either general or local planation. Thus wind and water are very much alike in some of their general leveling effects (plate 41, figure 1) from photograph by U. S. Geological Survey.

NORMAL TORRENTIAL ACTION OF WATER IN THE MOUNTAINS

In the higher mountains of the arid region the torrential effects of water are not very different from what they are in the more humid regions. Whatever the effects of wind erosion there are they are largely obscured by the exceptionally heavy precipitation. The Tijeras creek and the Rio Galisteo are good examples.

FREQUENT OCCUPATION OF PLAINS BY LAKES

Intermont plains often contain somewhere within their boundaries lakes, playas, and salinas, the waters of which are quite ephemeral in character. Many, and perhaps all, of these shallow lake-basins are hollowed out of the plains-floor by the wind. Laguna del Perro, and other lakelets of the Estancia plains (plate 41, figure 2), the gypsum sands district of the Hueco bolson and the Playa de los Pinos are typical.

MARKED ABSENCE OF ROCK-WEATHERING

The extent, rapidity, and character of rock-decomposition such as takes place in the humid regions is in the arid country almost unknown. Rocks of all kinds exhibit little or no weathering. Their surfaces are characterized by their wonderful freshness. This feature is best shown in the huge igneous masses of the Cerrillos hills.

REMARKABLE THINNESS OF SURFACE MANTLE

The loam and débris covering the plains is unexpectedly thin, usually occurring only as a veneer. This is typically displayed along the Rio Galisteo and the Arroyo San Pedro east of the Sandia range. (See plate 40, figure 2, from photograph by D. W. Johnson.) The Sonoran plains, described by McGee,[7] further attest the general prevalency of the phenomenon.

TRANSPORTED NATURE OF THE SURFACE MATERIALS

All of the finer detritus is manifestly far removed from its original location. It appears to be a very rare occurrence for the surface materials of the plains to give any suggestion of the rock-composition beneath. The mesa above Albuquerque illustrates the point.

GRAVELLY CHARACTER OF SURFACE DEPOSITS LARGELY ONLY APPARENT

Predominance of gravels on the surface of the plains is illusory. The mantle is mainly loamy. It is not generally recognized that the great abundance

[7] Bulletin of the Geological Society of America, vol. 8, 1897, p. 91.

FIGURE 1.—PLATEAU PLAIN NEAR ZUÑI, NEW MEXICO

Basalt capped mesa, 600 feet above plain

FIGURE 2.—WIND-SCOURED LAKE BASINS OF ESTANCIA PLAINS, NEW MEXICO

CONTRASTS OF DEFLATIVE EROSION

of pebbles on the surface is due principally to the fact that the wind blows away the finer materials. Most of the gravel-surfaced mesas when upturned by the plow give excellent loamy fields. The most notable examples on an extensive scale are shown in the Estancia valley.

TENDENCY OF MANTLE TO MAKE THE PLAINS EVEN

While the rock-floor of the plains is a plain itself, there are many minor irregularities in the rock-surface. Between sheetflood transportation and wind-drifted loams and sands these depressions are quickly filled up. The soft mantle only makes the plains smoother. The nearest point where this phenomenon is clearly shown is in the vicinity of Los Cerrillos.

ABSENCE OF DISTINCT WATERWAYS ON THE PLAINS

Soon after leaving the foot of the mountains the drainage-lines entirely disappear. Although the gradients are high, no drainage-systems are developed. When channel-ways are corraded by unusual freshets in the mountains they are quickly filled up by drifting sands. In the San Pedro arroyo this vanishing of the drainage-ways is finely displayed.

RÔLE OF SHEETFLOOD ACTION

Sheetflood action is one of the most important of the plains-forming agencies. Instead of water even tending to concentrate along certain lines, as in the humid regions, heavy local rainfall in the mountains spreads out on reaching the margins of the plains. Slight inequalities tend to become obliterated by the effects of the sheetflood.

LACK OF DIRECT EVIDENCE OF FORMER HUMID CLIMATE

In the New Mexican region there are discernible no facts suggesting a climate at no distant period of much greater humidity than at present. In the Nevada region the main moulding of mountain and valley has recently been ascribed to former greater rainfall and consequent more adequate water erosion. Independent of any such change of climate the known erosional effects of the winds under conditions of an arid climate may be considered amply sufficient to account for all features of the present landscape.

The next paper read was

SHORELINE STUDIES ON LAKES ONTARIO AND ERIE

BY ALFRED W. G. WILSON

The paper has been published as pages 471-500 of this volume.

The following papers were then read by title:

FAULTS AND FOLDS OF THE GRAND CANYON DISTRICT

BY DOUGLAS WILSON JOHNSON

COON BUTTE, ARIZONA

BY JOHN B. HASTINGS

OCCURRENCE OF PETROLEUM IN THE COAST COUNTIES OF CALIFORNIA

BY RALPH ARNOLD

CONGLOMERATE FORMED BY A MINERAL-LADEN STREAM IN CALIFORNIA

BY R. ARNOLD AND R. ANDERSON

This paper has been published as pages 147-154 of this volume.

DISTRIBUTION OF GOLD IN THE SADDLE AND LEG REGION OF THE MEGUMA SERIES OF NOVA SCOTIA

BY J. EDMUND WOODMAN

PROBABLE AGE OF THE MEGUMA (GOLD-BEARING) SERIES OF NOVA SCOTIA

J. EDMUND WOODMAN

This paper was printed as pages 99-112 of this volume.

GIANT SPRINGS AT GREAT FALLS, MONTANA

BY C. A. FISHER[1]

This paper was printed as pages 339-346 of this volume.

After the end of the reading of formal papers, C. W. Hayes informally exhibited a set of photographs of the fossil woods of Arizona, together with notes on them by David White, paleobotanist to the United States Geological Survey. Then W. G. Tight exhibited and described a series of stereopticon slides illustrating glacial and other phenomena among the high Andes of Bolivia, and the scientific program was declared finished.

COMMITTEE ON GEOLOGICAL NOMENCLATURE

The question of forming a General Committee on Geological Nomenclature was thoroughly discussed by C. R. Van Hise, A. C. Lane, A. C. Lawson, A. P. Coleman, G. K. Gilbert, H. E. Gregory, R. D. George, C. W. Hayes, and W. G. Tight, and the following action was taken unanimously:

The Geological Society of America recommends to the various organizations concerned:

1. That a general Committee on Geological Nomenclature be formed; one-fifth of its members to be from the United States Geological Survey, one-fifth from the Canadian Geological Survey organizations, one-fifth

[1] Introduced by C. W. Hayes.

from Mexico, and one-fifth from geologists at large selected by the Geological Society of America.

2. That this general committee have authority to appoint special committees on nomenclature from within or without its own membership for the investigation of the particular questions referred to them, the special committees to report back their conclusions to the general committee with full reasons therefor; the different sections to report in turn to their own organizations.

3. That the fact that any subject is under discussion by this general committee be made known to the scientific public at large.

The purpose of the recommendations is to provide a source from which any geologist may on application obtain advice regarding nomenclature.

The following resolutions of thanks were presented by G. K. Gilbert, seconded by President Van Hise and heartily adopted:

The Geological Society of America acknowledges with gratitude the many and substantial courtesies extended to it by the citizens and the Commercial Club of the city of Albuquerque.

The Society also tenders its sincere and emphatic thanks to the University of New Mexico, and particularly to President W. G. Tight, for the hospitality it has enjoyed—a hospitality which included arrangements of exceptional completeness and attentions most assiduous.

Register of the Albuquerque Meeting, 1907.

The following Fellows were in attendance at the meeting:

H. M. Ami.
R. W. Brock.
Samuel Calvin.
A. P. Coleman.
George E. Collie.
F. W. Cragin.
H. P. Cushing.
J. S. Diller.
R. D. George.
G. K. Gilbert.
Herbert E. Gregory.
G. D. Harris.
C. W. Hayes.
E. O. Hovey.
Alfred C. Lane.
Andrew C. Lawson.
George D. Louderback.
Arthur M. Miller.
W. G. Miller.
H. B. Patton.
A. H. Purdue.
W. G. Tight.
Charles R. Van Hise.
Frank R. Van Horn.
T. L. Walker.
I. C. White.
A. W. G. Wilson.
John E. Wolff.

There were in addition at least five visiting geologists, not members of the Society, besides students and casual visitors.

Session of the Cordilleran Section, Tuesday, December 31, 1907.

The Cordilleran Section met with the general Society. On Tuesday, December 31, the section held a business session, at which Andrew C. Lawson and George D. Louderback were reëlected chairman and secretary respectively.

ACCESSIONS TO LIBRARY FROM NOVEMBER, 1907, TO NOVEMBER, 1908

By H. P. Cushing, *Librarian*

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3388. Publication no. 6.

(*b*) *EUROPE*

SCHLESISCHE GESELLSCHAFT FÜR VATERLÄNDISCHE CULTUR, BRESLAU

3231. Eighty-fourth Jahresbericht, 1905.

OBSERVATOIRE ROYAL DE BELGIQUE, BRUSSELS

3389. Annuaire Astronomique, 1907.
3211. Les Observatoires Astronomiques et les Astronomes.

INSTITUTUL GEOLOGIE AL ROUMANIEI, BUCHAREST

3232. Anuarul, vol. i, fasc. 1-2.
Anuarul, vol. i, fasc. 3.

DANSK GEOLOGISK FORENING, COPENHAGEN

2783. Meddelelser, nr. 13.

SENCKENBERGISCHEN NATURFORSCHENDEN GESELLSCHAFT, FRANKFURT AM MAIN

3390. Bericht, 1907.

MUSÉE TEYLER, HAARLEM

3391. Archives, serie ii, vol. xi, part 1.

LA SOCIÉTÉ PORTUGAISE DE SCIENCES NATURELLES, LISBON

3392. Bulletin, vol. i, fasc. 1-3.

ACADEMIE POLYTECHNICA, PORTO

3182. Annaes Scientificos, vol. ii, no. 4.
3335. Annaes Scientificos, vol. iii, no. 1.

CORPO REALE DELLE MINIERE, ROME

3354. Carta geologica delle Alpi Occidentali.

INSTITUT DES MINES DE L'IMPERATRICE CATHERINE II, SAINT PETERSBURG

3270. Annales, tome i, no. 1.

(c) *ASIA*

TOKYO GEOGRAPHICAL SOCIETY, TOKYO

3206. Journal of Geography, vol. xix, 1907.

IMPERIAL UNIVERSITY OF TOKYO, TOKYO

3201. Journal of the College of Science, vol. xxii, articles 8 and 9.

(*D*) FROM FELLOWS OF THE GEOLOGICAL SOCIETY OF AMERICA (PERSONAL PUBLICATIONS)

CROOK, A. R.

3393. A History of the Illinois State Museum of Natural History.

FAIRCHILD, H. L.

3394. Gilbert Gulf (Marine Waters in Ontario Basin).
3395. Drumlin Structure and Origin.

WALCOTT, CHARLES D.

3396. Cambrian Geology and Paleontology, nos. 3-4.

(*E*) FROM MISCELLANEOUS SOURCES

HEIM, ALBRECHT

3397. Der Bau der Schweizeralpen.

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FELLOWS IN DECEMBER, 1908

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Cleveland Abbe, Jr., Ph. D., Mount Weather, Va. August, 1899.

Frank Dawson Adams, Ph. D., Montreal, Canada; Professor of Geology in McGill University. December, 1889.

George I. Adams, Sc. D., Bureau of Mines, Manila, P. I. December, 1902.

José Guadalupe Aguilera, City of Mexico, Mexico; Director del Instituto Geologico de Mexico. August, 1896.

Truman H. Aldrich, M. E., 1739 P St. N. W., Washington, D. C. May, 1889.

Henry M. Ami, A. M., Montreal, Canada; Assistant Paleontologist on Geological and Natural History Survey of Canada. December, 1889.

Frank M. Anderson, B. A., M. S., 2604 Ætna Street, Berkeley, Cal. California State Mining Bureau. June, 1902.

Philip Argall, 728 Majestic Building, Denver, Colo. August, 1896.

Ralph Arnold, Ph. D., Washington, D. C.; Geologic Aid, U. S. Geological Survey. December, 1904.

George Hall Ashley, M. E., Ph. D., Washington, D. C.; U. S. Geological Survey. August, 1895.

Rufus Mather Bagg, Jr., Ph. D., 1048 Riverdale St., West Springfield, Mass. December, 1896.

Harry Foster Bain, M. S., Champaign, Ill.; State Geologist. December, 1895.

S. Prentiss Baldwin, 736 Prospect St., Cleveland, Ohio. August, 1895.

Sydney H. Ball, A. B., Washington, D. C.; Assistant Geologist, U. S. Geological Survey. December, 1905.

Erwin Hinckley Barbour, Ph. D., Lincoln, Neb.; Professor of Geology, University of Nebraska, and Acting State Geologist. December, 1896.

Alfred Ernest Barlow, B. A., M. A., D. Sc., Ottawa, Canada. December, 1906.

Joseph Barrell, Ph. D., New Haven, Conn.; Professor of Structural Geology, Yale University. December, 1902.

George H. Barton, B. S., Boston, Mass.; Curator, Boston Society of Natural History. August, 1890.

Florence Bascom, Ph. D., Bryn Mawr, Pa.; Professor of Geology, Bryn Mawr College. August, 1894.

Ray Smith Bassler, B. A., M. S., Ph. D., Washington, D. C.; U. S. National Museum. December, 1906.

William S. Bayley, Ph. D., Urbana, Ill.; Assistant Professor of Geology, University of Illinois. December, 1888.

***George F. Becker, Ph. D., Washington, D. C.; U. S. Geological Survey.**

Joshua W. Beede, Ph. D., Bloomington, Ind.; Instructor in Geology, Indiana University. December, 1902.

Robert Bell, I. S. O., Sc. D., M. D., LL. D., F. R. S., Ottawa, Canada; Chief Geologist, Geological Survey, Department of Mines. May, 1889.

Charles P. Berkey, Ph. D., New York city; Columbia University. August, 1901.

Samuel Walker Beyer, Ph. D., Ames, Iowa; Assistant Professor in Geology, Iowa Agricultural College. December, 1896.

Arthur B. Bibbins, Ph. B., Baltimore, Md.; Instructor in Geology, Woman's College. December, 1903.

Albert S. Bickmore, Ph. D., New York city; Curator emeritus, Department of Public Instruction, American Museum of Natural History. December, 1889.

IRVING P. BISHOP, 109 Norwood Ave., Buffalo, N. Y.; Professor of Natural Science, State Normal and Training School. December, 1899.

JOHN M. BOUTWELL, M. S., Washington, D. C.; Assistant Geologist, U. S. Geological Survey. December, 1905.

JOHN ADAMS BOWNOCKER, D. Sc., Columbus, Ohio.; Professor of Inorganic Geology, Ohio State University. December, 1904.

*JOHN C. BRANNER, Ph. D., Stanford University, Cal.; Professor of Geology in Leland Stanford, Jr., University.

ALBERT PERRY BRIGHAM, A. B., A. M., Hamilton, N. Y.; Professor of Geology and Natural History, Colgate University. December, 1893.

REGINALD W. BROCK, M. A., Ottawa, Canada; Acting Director, Geological Survey, Department of Mines. December, 1904.

ALFRED HULSE BROOKS, B. S., Washington, D. C.; Assistant Geologist, U. S. Geological Survey. August, 1899.

AMOS P. BROWN, Ph. D., Philadelphia, Pa.; Professor of Mineralogy and Geology, University of Pennsylvania. December, 1905.

ERNEST ROBERTSON BUCKLEY, Ph. D., Flat River, Mo. June, 1902.

*SAMUEL CALVIN, Iowa City, Iowa; Professor of Geology and Zoology in the State University of Iowa.

HENRY DONALD CAMPBELL, Ph. D., Lexington, Va.; Professor of Geology and Biology in Washington and Lee University. May, 1889.

MARIUS R. CAMPBELL, Washington, D. C.: U. S. Geological Survey. Aug., 1892.

FRANKLIN R. CARPENTER, Ph. D., 1420 Josephine St., Denver, Colo. May, 1889.

ERMINE C. CASE, Ph. D., Ann Arbor, Mich.; Department of Geology, University of Michigan. December, 1901.

*T. C. CHAMBERLIN, LL. D., Chicago, Ill.; Head Professor of Geology, University of Chicago.

CLARENCE RAYMOND CLAGHORN, B. S., M. E., Tacoma, Wash. August, 1891.

FREDERICK G. CLAPP, S. B., 610 Fitzsimons Building, Pittsburgh, Pa. Dec., 1905.

*WILLIAM BULLOCK CLARK, Ph. D., Baltimore, Md.; Professor of Geology in Johns Hopkins University; State Geologist.

JOHN MASON CLARKE, A. M., Albany, N. Y.; State Paleontologist. December, 1897.

HERDMAN F. CLELAND, Ph. D., Williamstown, Mass.; Professor of Geology, Williams College. December, 1905.

J. MORGAN CLEMENTS, Ph. D., 15 William St., New York city. December, 1894.

COLLIER COBB, A. B., A. M., Chapel Hill, N. C.; Professor of Geology in University of North Carolina. December, 1894.

ARTHUR P. COLEMAN, Ph. D., Toronto, Canada; Professor of Geology, Toronto University, and Geologist of Bureau of Mines of Ontario. December, 1896.

GEORGE L. COLLIE, Ph. D., Beloit, Wis.; Professor of Geology in Beloit College. December, 1897.

ARTHUR J. COLLIER, A. M., S. B., Brownfield, Me.; Assistant Geologist, U. S. Geological Survey. June, 1902.

*THEODORE B. COMSTOCK, Sc. D., Los Angeles, Cal.

EUGENE COSTE, B. ès-Sc., E. M., Toronto, Canada. December, 1906.

*FRANCIS W. CRAGIN, Ph. D., Colorado Springs, Colo.; Professor of Geology in Colorado College.

ALJA ROBINSON CROOK, Ph. D., Springfield, Ill.; State Museum of Natural History. December, 1898.

*WILLIAM O. CROSBY, B. S., Boston, Mass.; Professor of Geology in Massachusetts Institute of Technology.

WHITMAN CROSS, Ph. D., Washington, D. C.; U. S. Geological Survey. May, 1889.

GARRY E. CULVER, A. M., 1104 Wisconsin St., Stevens Point, Wis. December, 1891.

EDGAR R. CUMINGS, Ph. D., Bloomington, Ind.; Assistant Professor of Geology, Indiana University. August, 1901.

*HENRY P. CUSHING, M. S., Adelbert College, Cleveland, Ohio; Professor of Geology, Western Reserve University.

REGINALD A. DALY, Ph. D., Boston, Mass.; Massachusetts Institute of Technology. December, 1905.

*NELSON H. DARTON, Washington, D. C.; U. S. Geological Survey.

*WILLIAM M. DAVIS, S. B., M. E., Cambridge, Mass.; Sturgis-Hooper Professor of Geology in Harvard University.

DAVID T. DAY, Ph. D., Washington, D. C.; U. S. Geological Survey. Aug., 1891.

ORVILLE A. DERBY, M. S., No. 80 Rua Visconde do Rio Branco, Sao Paulo, Brazil. December, 1890.

*JOSEPH S. DILLER, B. S., Washington, D. C.; U. S. Geological Survey.

EDWARD V. D'INVILLIERS, E. M., 506 Walnut St., Philadelphia, Pa. Dec., 1888.

RICHARD E. DODGE, A. M., New York city; Professor of Geography in the Teachers' College. August, 1897.

NOAH FIELDS DRAKE, Ph. D., Tientsin, China; Professor of Geology in Imperial Tientsin University. December, 1898.

JOHN ALEXANDER DRESSER, B. A., M. A., Montreal, Canada; Department of Geology, McGill University. December, 1906.

CHARLES R. DRYER, M. A., M. D., Terre Haute, Ind.; Professor of Geography, Indiana State Normal School. August, 1897.

*EDWIN T. DUMBLE, 1306 Main St., Houston, Texas.

CLARENCE EDWARD DUTTON, A. B., Englewood, N. J.; Major, U. S. A. (Retired). December, 1907.

ARTHUR S. EAKLE, Ph. D., Berkeley, Cal.; Instructor in Mineralogy, University of California. December, 1899.

CHARLES R. EASTMAN, A. M., Ph. D., Cambridge, Mass.; In Charge of Vetebrate Paleontology,. Museum of Comparative Zoology, Harvard University. December, 1895.

EDWIN C. ECKEL, B. S., C. E., Munsey Building, Washington, D. C. Dec., 1905.

ARTHUR H. ELFTMAN, Ph. D., 706 Globe Building, Minneapolis, Minn. December, 1898.

*BENJAMIN K. EMERSON, Ph. D., Amherst, Mass.; Professor in Amherst College.

*SAMUEL F. EMMONS, A. M., E. M., Washington, D. C.; U. S. Geological Survey.

JOHN EYERMAN, F. Z. S., Oakhurst, Easton, Pa. August, 1891.

HAROLD W. FAIRBANKS, B. S., Berkeley, Cal.; Geologist State Mining Bureau. August, 1892.

*HERMAN L. FAIRCHILD, B. S., Rochester, N. Y.; Professor of Geology in University of Rochester.

J. C. FALES, Danville, Ky.; Professor in Centre College. December, 1888.

OLIVER C. FARRINGTON, Ph. D., Chicago, Ill.; Curator of Geology, Field Museum of Natural History. December, 1895.

NEVIN M. FENNEMAN, Ph. D., Cincinnati, Ohio; Professor of Geology, University of Cincinnati. December, 1904.

AUGUST F. FOERSTE, Ph. D., 417 Grand Ave., Dayton, Ohio; Teacher of Sciences, Steele High School. December, 1899.

WILLIAM M. FONTAINE, A. M., Charlottesville, Va.; Professor of Natural History and Geology in University of Virginia. December, 1888.

*PERSIFOR FRAZER, D. ès-Sc. Nat., 1082 Drexel Building, Philadelphia, Pa.; Professor of Chemistry in Horticultural Society of Pennsylvania.

MYRON LESLIE FULLER, S. B., 104 Belmont Ave., Brockton, Mass. Dec., 1898.

HENRY STEWART GANE, Ph. D., Santa Barbara, Cal. December, 1896.

HENRY GANNETT, S. B., A. Met. B., Washington, D. C.; U. S. Geological Survey. December, 1891.

RUSSELL D. GEORGE, A. B., A. M., Boulder, Colo.; Professor of Geology, University of Colorado. December, 1906.

*GROVE K. GILBERT, A. M., LL. D., Washington, D. C.; U. S. Geological Survey.

ADAM CAPEN GILL, Ph. D., Ithaca, N. Y.; Assistant Professor of Mineralogy and Petrography in Cornell University. December, 1888.

L. C. GLENN, Ph. D., Nashville, Tenn.; Professor of Geology in Vanderbilt University. June, 1900.

CHARLES H. GORDON, Ph. D., Knoxville, Tenn.; Professor of Geology and Mineralogy in the University of Tennessee. August, 1893.

CHARLES NEWTON GOULD, A. M., Norman, Okla.; Professor of Geology, University of Oklahoma. December, 1904.

AMADEUS W. GRABAU, S. M., S. D., New York city; Professor of Paleontology, Columbia University. December, 1898.

ULYSSES SHERMAN GRANT, Ph. D., Evanston, Ill.; Professor of Geology, Northwestern University. December, 1890.

HERBERT E. GREGORY, Ph. D., New Haven, Conn.; Silliman Professor of Geology, Yale University. August, 1901.

GEORGE P. GRIMSLEY, Ph. D., Morgantown, W. Va.; Assistant State Geologist, Geological Survey of West Virginia. August, 1895.

LEON S. GRISWOLD, A. B., Rolla, Missouri. August, 1902.

FREDERIC P. GULLIVER, Ph. D., Norwichtown, Conn. August, 1895.

ARNOLD HAGUE, Ph. B., Washington, D. C.; U. S. Geological Survey. May, 1889.

*CHRISTOPHER W. HALL, A. M., 803 University Ave., Minneapolis, Minn.; Professor of Geology and Mineralogy in University of Minnesota.

GILBERT D. HARRIS, Ph. B., Ithaca, N. Y.; Assistant Professor of Paleontology and Stratigraphic Geology, Cornell University. December, 1903.

JOHN BURCHMORE HARRISON, M. A., F. I. C., F. G. S., Georgetown, British Guiana; Government Geologist. June, 1902.

JOHN B. HASTINGS, M. E., 1480 High St., Denver, Colo. May, 1889.

*ERASMUS HAWORTH, Ph. D., Lawrence, Kans.; Professor of Geology, University of Kansas.

C. WILLARD HAYES, Ph. D., Washington, D. C.; U. S. Geological Survey. May, 1889.

RICHARD R. HICE, B. S., Beaver, Pa. December, 1903.

*EUGENE W. HILGARD, Ph. D., LL. D., Berkeley, Cal.; Professor of Agriculture in University of California.

FRANK A. HILL, Roanoke, Va. May, 1889.

*ROBERT T. HILL, B. S., 25 Broad St., New York city.

RICHARD C. HILLS, Denver, Colo. August, 1894.

*CHARLES H. HITCHCOCK, Ph. D., LL. D., Honolulu, Hawaiian Islands; Professor Emeritus of Geology in Dartmouth College, Hanover, N. H.

WILLIAM HERBERT HOBBS, Ph. D., Ann Arbor, Mich.; Professor of Geology, University of Michigan; Assistant Geologist, U. S. Geological Survey. August, 1891.

*LEVI HOLBROOK, A. M., P. O. Box 536, New York city.

ARTHUR HOLLICK, Ph. B., Bronx Park, New York; Assistant Curator, Department of Fossil Botany, New York Botanical Garden. August, 1893.

*JOSEPH A. HOLMES, Washington, D. C.; in charge of investigation of fuels and structural materials, U. S. Geological Survey.

THOMAS C. HOPKINS, Ph. D., Syracuse, N. Y.; Professor of Geology, Syracuse University. December, 1894.

*EDMUND OTIS HOVEY, Ph. D., New York city; Associate Curator of Geology, American Museum of Natural History.

*HORACE C. HOVEY, D. D., Newburyport, Mass.

ERNEST HOWE, Ph. D., Newport, R. I.; Assistant Geologist, U. S. Geological Survey. December, 1903.

*EDWIN E. HOWELL, A. M., 612 Seventeenth St. N. W., Washington, D. C.

LUCIUS L. HUBBARD, Ph. D., LL. D., Houghton, Mich. December, 1894.

ELLSWORTH HUNTINGTON, A. B., A. M., Milton, Mass. December, 1906.

JOSEPH P. IDDINGS, Ph. B., Chicago, Ill.; Professor of Petrographic Geology, University of Chicago. May, 1889.

JOHN D. IRVING, Ph. D., New Haven, Conn.; Professor of Economic Geology, Yale University. December, 1905.

A. WENDELL JACKSON, Ph. B., 432 Saint Nicholas Ave., New York city. December, 1888.

ROBERT T. JACKSON, S. D., 9 Fayerweather St., Cambridge, Mass.; Assistant Professor in Paleontology in Harvard University. August, 1894.

THOMAS M. JACKSON, C. E., S. D., Clarksburg, W. Va. May, 1889.

THOMAS AUGUSTUS JAGGAR, JR., A. B., A. M., Ph. D., Boston, Mass.; Professor of Geology, Massachusetts Institute of Technology. December, 1906.

MARK S. W. JEFFERSON, A. M., Ypsilanti, Mich.; Professor of Geography, Michigan State Normal College. December, 1904.

DOUGLAS WILSON JOHNSON, B. S., Ph. D., Cambridge, Mass.; Assistant Professor of Physiography, Harvard University. December, 1906.

ALEXIS A. JULIEN, Ph. D., New York city; Curator in Geology in Columbia University. May, 1889.

ARTHUR KEITH, A. M., Washington, D. C.; U. S. Geological Survey. May, 1889.

*JAMES F. KEMP, A. B., E. M., New York city; Professor of Geology in Columbia University.

CHARLES ROLLIN KEYES, Ph. D., 944 Fifth St., Des Moines, Iowa. August, 1890.

EDWARD M. KINDLE, Ph. D., Washington, D. C.; Assistant Geologist, U. S. Geological Survey. December, 1905.

FRANK H. KNOWLTON, M. S., Washington, D. C.; Assistant Paleontologist, U. S. Geological Survey. May, 1889.

EDWARD HENRY KRAUS, Ph. D., Ann Arbor, Mich.; Junior Professor of Mineralogy, University of Michigan. June, 1902.

HENRY B. KUMMEL, Ph. D., Trenton, N. J.; State Geologist. December, 1895.

*GEORGE F. KUNZ, A. M. (Hon.), Ph. D. (Hon.), care of Tiffany & Co., Fifth avenue, at 37th street, New York city.

GEORGE EDGAR LADD, Ph. D., Rolla, Mo.; Director School of Mines. August, 1891.

J. C. K. LAFLAMME, M. A., D. D., Quebec, Canada; Professor of Mineralogy and Geology in Laval University, Quebec. August, 1890.

ALFRED C. LANE, Ph. D., Lansing, Mich.; State Geologist. December, 1889.

DANIEL W. LANGTON, Ph. D., Fuller Building, New York city. December, 1889.

ANDREW C. LAWSON, Ph. D., Berkeley, Cal.; Professor of Geology and Mineralogy in the University of California. May, 1889.

WILLIS THOMAS LEE, M. S., Washington, D. C.; Assistant Geologist, U. S. Geological Survey. December, 1903.

CHARLES K. LEITH, Ph. D., Madison, Wis.; Professor of Geology, University of Wisconsin; Assistant Geologist, U. S. Geological Survey. December, 1902.

ARTHUR G. LEONARD, Ph. D., Grand Forks, N. Dak.; Professor of Geology and State Geologist, State University of North Dakota. December, 1901.

Frank Leverett, B. S., Ann Arbor, Mich.; Geologist, U. S. Geological Survey. August, 1890.

Joseph Volney Lewis, B. E., S. B., New Brunswick, N. J.; Professor of Geology, Rutgers College. December, 1906.

William Libbey, Sc. D., Princeton, N. J.; Professor of Physical Geography in Princeton University. August, 1899.

Waldemar Lindgren, M. E., Washington, D. C.; U. S. Geological Survey. August. 1890.

George Davis Louderback, Ph. D., Berkeley, Cal.; Associate Professor of Geology, University of California. June, 1902.

Robert H. Loughridge, Ph. D., Berkeley, Cal.; Assistant Professor of Agricultural Chemistry in University of California. May, 1889.

Albert P. Low, B. A. Sc., LL. D., Ottawa, Canada; Deputy Minister, Department of Mines. December, 1905.

Thomas H. Macbride, A. M., Iowa City, Iowa; Professor of Botany in the State University of Iowa. May, 1889.

Hiram Deyer McCaskey, B. S., Washington, D. C.; U. S. Geological Survey. December, 1904.

Richard G. McConnell, A. B., Ottawa, Canada; Geologist on Geological and Natural History Survey of Canada. May, 1889.

James Rieman Macfarlane, A. B., 100 Diamond St., Pittsburg, Pa. August 1891.

*W J McGee, LL. D., Washington, D. C.; Inland Waterways Commission.

William McInnes, A. B., Ottawa, Canada; Geologist, Geological and Natural History Survey of Canada. May, 1889.

Peter McKellar, Fort William, Ontario, Canada. August, 1890.

Curtis F. Marbut, A. M., Columbia, Mo.; Instructor in Geology in State University and Assistant on Missouri Geological Survey. August, 1897.

Vernon F. Marsters, A. M., Apartado 856, Lima, Peru. August, 1892.

George Curtis Martin, Ph. D., Washington, D. C.; U. S. Geological Survey. June, 1902.

Edward B. Mathews, Ph. D., Baltimore, Md.; Professor of Mineralogy and Petrography in Johns Hopkins University. August, 1895.

W. D. Matthew, Ph. D., New York city; Associate Curator of Vertebrate Paleontology, American Museum of Natural History. December, 1903.

P. H. Mell, M. E., Ph. D., Clemson College, S. C.; President of Clemson College. December, 1888.

Walter C. Mendenhall, B. S., Washington, D. C.; Geologist, U. S. Geological Survey. June, 1902.

John C. Merriam, Ph. D., Berkeley, Cal.; Instructor in Paleontology in University of California. August, 1895.

*Frederick J. H. Merrill, Ph. D., New Rochelle, N. Y.

George P. Merrill, Ph. D., Washington, D. C.; Curator of Department of Lithology and Physical Geology in U. S. National Museum. Dec., 1888.

Arthur M. Miller, A. M., Lexington, Ky.; Professor of Geology, State University of Kentucky. December, 1897.

Benjamin L. Miller, Ph. D., South Bethlehem, Pa.; Professor of Geology, Lehigh University. December, 1904.

Willet G. Miller, M. A., Toronto, Canada; Provincial Geologist of Ontario. December, 1902.

Henry Montgomery, Ph. D., Toronto, Canada; Curator of Museum, University of Toronto. December, 1904.

*Frank L. Nason, A. B., West Haven, Conn.

David Hale Newland, B. A., Albany, N. Y.; Assistant State Geologist. December, 1906.

JOHN F. NEWSOM, Ph. D., Stanford University, Cal.; Associate Professor of Mining in Leland Stanford, Jr., University. December, 1899.

WILLIAM H. NILES, Ph. B., M. A., Boston, Mass.; Professor Emeritus of Geology, Massachusetts Institute of Technology; Professor of Geology, Wellesley College. August, 1891.

WILLIAM H. NORTON, M. A., Mount Vernon, Iowa; Professor of Geology in Cornell College. December, 1895.

CHARLES J. NORWOOD, Lexington, Ky.; Professor of Mining, State University of Kentucky. August, 1894.

IDA HELEN OGILVIE, A. B., Ph. D., New York city; Tutor in Geology, Barnard College, Columbia University. December, 1906.

CLEOPHAS C. O'HARRA, Ph. D., Rapid City, S. Dak.; Professor of Mineralogy and Geology, South Dakota School of Mines. December, 1904.

EZEQUIEL ORDONEZ, 2 a General Prine, Mexico, D. F., Mex. August, 1896.

*AMOS O. OSBORN, Waterville, Oneida county, N. Y.

HENRY F. OSBORN, Sc. D., New York city; President of the American Museum of Natural History. August, 1894.

CHARLES PALACHE, B. S., Cambridge, Mass.; Instructor in Mineralogy, Harvard University. August, 1897.

WILLIAM A. PARKS, B. A., Ph. D., Toronto, Canada; Associate Professor of Geology, University of Toronto. December, 1906.

*HORACE B. PATTON, Ph. D., Golden, Colo.; Professor of Geology and Mineralogy in Colorado School of Mines.

FREDERICK B. PECK, Ph. D., Easton, Pa.; Professor of Geology and Mineralogy, Lafayette College. August, 1901.

RICHARD A. F. PENROSE, JR., Ph. D., 460 Bullitt Building, Philadelphia, Pa. May, 1889.

DAVID PEARCE PENHALLOW, B. S., M. S., Sc. D., Montreal, Canada; Professor of Botany in McGill University. December, 1907.

GEORGE H. PERKINS, Ph. D., Burlington, Vt.; State Geologist; Professor of Geology, University of Vermont. June, 1902.

JOSEPH H. PERRY, 276 Highland St., Worcester, Mass. December, 1888.

LOUIS V. PIRSSON, Ph. D., New Haven, Conn.; Professor of Physical Geology, Sheffield Scientific School of Yale University. August, 1894.

*JULIUS POHLMAN, M. D., University of Buffalo, Buffalo, N. Y.

JOSEPH HYDE PRATT, Ph. D., Chapel Hill, N. C.; Mineralogist, North Carolina Geological Survey. December, 1898.

*CHARLES S. PROSSER, M. S., Columbus, Ohio; Professor of Geology in Ohio State University.

*RAPHAEL PUMPELLY, Newport, R. I.

ALBERT HOMER PURDUE, B. A., Fayetteville, Ark.; Professor of Geology, University of Arkansas. December, 1904.

FREDERICK LESLIE RANSOME, Ph. D., Washington, D. C.; Geologist, U. S. Geological Survey. August, 1895.

PERCY EDWARD RAYMOND, B. A., Ph. D., Pittsburgh, Pa.; Assistant Curator of Invertebrate Fossils in the Carnegie Museum. December, 1907.

HARRY FIELDING REID, Ph. D., Baltimore, Md.; Professor of Geological Physics, Johns Hopkins University. December, 1892.

WILLIAM NORTH RICE, Ph. D., LL. D., Middletown, Conn.; Professor of Geology in Wesleyan University. August, 1890.

CHARLES H. RICHARDSON, Ph. D., Syracuse, N. Y.; Assistant Professor of Geology and Mineralogy, Syracuse University. December, 1899.

HEINRICH RIES, Ph. D., Ithaca, N. Y.; Professor of Economic Geology in Cornell University. December, 1893.

RUDOLPH RUEDEMANN, Ph. D., Albany, N. Y.; Assistant State Paleontologist. December, 1905.

ORESTES H. ST. JOHN, 1318 West 6th St., Topeka, Kansas. May, 1889.

*ROLLIN D. SALISBURY, A. M., Chicago, Ill.; Professor of General and Geographic Geology in University of Chicago.

FREDERICK W. SARDESON, Ph. D., Minneapolis, Minn.; Assistant Professor of Geology, University of Minnesota. December, 1892.

THOMAS EDMUND SAVAGE, A. B., B. S., M. S., Urbana, Ill.; Department of Geology, University of Illinois. December, 1907.

FRANK C. SCHRADER, M. S., A. M., Washington, D. C.; U. S. Geological Survey. August, 1901.

CHARLES SCHUCHERT, New Haven, Conn.; Professor of Paleontology, Yale University. August, 1895.

WILLIAM B. SCOTT, Ph. D., 56 Bayard Ave., Princeton, N. J.; Blair Professor of Geology in Princeton University. August, 1892.

ARTHUR EDMUND SEAMAN, B. S., Houghton, Mich.; Professor of Mineralogy and Geology, Michigan College of Mines. December, 1904.

HENRY M. SEELY, M. D., Middlebury, Vt.; Professor of Geology in Middlebury College. May, 1899.

ELIAS H. SELLARDS, Ph. D., Tallahassee, Fla.; State Geologist. December, 1905.

GEORGE BURBANK SHATTUCK, Ph. D., Poughkeepsie, N. Y.; Professor of Geology in Vassar College. August, 1899.

SOLON SHEDD, A. B., Pullman, Wash.; Professor of Geology and Mineralogy, Washington Agricultural College. December, 1904.

EDWARD M. SHEPARD, Sc. D., Springfield, Mo.; Professor of Geology, Drury College. August, 1901.

WILL H. SHERZER, M. S., Ypsilanti, Mich.; Professor in State Normal School. December, 1890.

BOHUMIL SHIMEK, C. E., M. S., Iowa City, Iowa; Professor of Physiological Botany, University of Iowa. December, 1904.

*FREDERICK W. SIMONDS, Ph. D., Austin, Texas; Professor of Geology in University of Texas.

WILLIAM JOHN SINCLAIR, B. S., Ph. D., Princeton, N. J.; Instructor in Princeton University. December, 1906.

*EUGENE A. SMITH, Ph. D., University, Tuscaloosa county, Ala.; State Geologist and Professor of Chemistry and Geology in University of Alabama.

FRANK CLEMES SMITH, E. M., Richland Center, Wis. December, 1898.

GEORGE OTIS SMITH, Ph. D., Washington, D. C.; Director, U. S. Geological Survey. August, 1897.

WILLIAM S. T. SMITH, Ph. D., 839 Lake St., Reno, Nev.; Associate Professor of Geology and Mineralogy, University of Nevada. June, 1902.

*JOHN C. SMOCK, Ph. D., Trenton, N. J.

CHARLES H. SMYTH, JR., Ph. D., Princeton, N. J.; Professor of Geology in Princeton University. August, 1892.

HENRY L. SMYTH, A. B., Cambridge, Mass.; Professor of Mining and Metallurgy in Harvard University. August, 1894.

ARTHUR COE SPENCER, B. S., Ph. D., Washington, D. C.; Assistant Geologist, U. S. Geological Survey. December, 1896.

*J. W. SPENCER, Ph. D., 2019 Hillyer Place, Washington, D. C.

JOSIAH E. SPURR, A. B., A. M., 165 Broadway, New York, N. Y. Dec., 1894.

JOSEPH STANLEY-BROWN, Cold Spring Harbor, Long Island, N. Y. August, 1892.

TIMOTHY WILLIAM STANTON, B. S., U. S. National Museum, Washington, D. C.; Assistant Paleontologist, U. S. Geological Survey. August, 1891.

*John J. Stevenson, Ph. D., LL. D., 568 West End avenue, New York, N. Y.

William J. Sutton, B. S., E. M., Victoria, B. C.; Geologist to E. and N. Railway Co. August, 1901.

Joseph A. Taff, B. S., Washington, D. C.; Assistant Geologist, U. S. Geological Survey. August, 1895.

James E. Talmage, Ph. D., Salt Lake City, Utah; Professor of Geology in University of Utah. December, 1897.

Ralph S. Tarr, Ithaca, N. Y.; Professor of Dynamic Geology and Physical Geography in Cornell University. August, 1890.

Frank B. Taylor, Fort Wayne, Ind. December, 1895.

William G. Tight, M. S., Albuquerque, N. Mex.; President and Professor of Geology, University of New Mexico. August, 1897.

*James E. Todd, A. M., 113 Park St., Lawrence, Kas.; Assistant Geologist, U. S. Geological Survey.

*Henry W. Turner, B. S., Room 709, Mills Building, San Francisco, Cal.

Joseph B. Tyrrell, M. A., B. Sc., 9 Toronto St., Toronto, Canada. May, 1889.

Johan A. Udden, A. M., Rock Island, Ill.; Professor of Geology and Natural History in Augustana College. August, 1897.

Edward O. Ulrich, D. Sc., Washington, D. C.; Assistant Geologist, U. S. Geological Survey. December, 1903.

*Warren Upham, A. M., Saint Paul, Minn.; Librarian Minnesota Historical Society.

*Charles R. Van Hise, M. S., Ph. D., Madison, Wis.; President University of Wisconsin; Geologist, U. S. Geological Survey.

Frank Robertson Van Horn, Ph. D., Cleveland, Ohio; Professor of Geology and Mineralogy, Case School of Applied Science. December, 1898.

Gilbert van Ingen, Princeton, N. J.; Curator of Invertebrate Paleontology and Assistant in Geology, Princeton University. December, 1904.

Thomas Wayland Vaughn, B. S., A. M., Washington, D. C.; Assistant Geologist, U. S. Geological Survey. August, 1896.

Arthur Clifford Veach, Washington, D. C.; Geologist, U. S. Geological Survey. December, 1906.

*Anthony W. Vogdes, 2425 First St., San Diego, Cal.; Brigadier General, U. S. A. (Retired).

*M. Edward Wadsworth, Ph. D., Pittsburgh, Pa.; Dean of the School of Mines in the University of Pittsburgh.

*Charles D. Walcott, LL. D., Washington, D. C.; Secretary Smithsonian Institution.

Thomas L. Walker, Ph. D., Toronto, Canada; Professor of Mineralogy and Petrography, University of Toronto. December, 1903.

Charles H. Warren, Ph. D., Boston, Mass.; Instructor in Geology, Massachusetts Institute of Technology. December, 1901.

Henry Stephens Washington, Ph. D., Locust, Monmouth Co., N. J.; August, 1896.

Thomas L. Watson, Ph. D., Charlottesville, Va.; Professor of Geology in University of Virginia. June, 1900.

Walter H. Weed, E. M., Norwalk, Conn. May, 1889.

Fred. Boughton Weeks, Washington, D. C.; Assistant Geologist, U. S. Geological Survey. December, 1903.

Samuel Weidman, Ph. D., Madison, Wis.; Geologist, Wisconsin Geological and Natural History Survey. December, 1903.

Stuart Weller, B. S., Chicago, Ill.; Associate Professor of Paleontologic Geology, University of Chicago. June, 1900.

Lewis G. Westgate, Ph. D., Delaware, Ohio; Professor of Geology, Ohio Wesleyan University.

THOMAS C. WESTON, care of A. Patton, Levis, Quebec, Canada. August, 1893.

DAVID WHITE, B. S., U. S. National Museum, Washington, D. C.; Geologist, U. S. Geological Survey. May, 1889.

*ISRAEL C. WHITE, Ph. D., Morgantown, W. Va.

*ROBERT P. WHITFIELD, A. M., New York city; Curator of Geology and Paleontology, American Museum of Natural History.

FRANK A. WILDER, Ph. D., North Holston, Smyth Co., Va. December, 1905.

*EDWARD H. WILLIAMS, JR., A. C., E. M., Andover, Mass.

*HENRY S. WILLIAMS, Ph. D., Ithaca, N. Y.; Professor of Geology and Head of Geological Department, Cornell University.

IRA A. WILLIAMS, M. Sc., Ames, Iowa; Teacher Iowa State College. December, 1905.

BAILEY WILLIS, Washington, D. C.; U. S. Geological Survey. December, 1889.

SAMUEL W. WILLISTON, Ph. D., M. D., Chicago, Ill.; Professor of Paleontology, University of Chicago. December, 1889.

ARTHUR B. WILLMOTT, M. A., Sault Ste. Marie, Ontario, Canada. December, 1899.

ALFRED W. G. WILSON, Ph. D., 197 Park Ave., Montreal, Ontario, Canada. June, 1902.

ALEXANDER N. WINCHELL, Doct. U. Paris, Madison, Wis.; Professor of Geology and Mineralogy, University of Wisconsin. August, 1901.

*HORACE VAUGHN WINCHELL, 505 Palace Building, Minneapolis, Minn.

*NEWTON H. WINCHELL, A. M., Minneapolis, Minn.

*ARTHUR WINSLOW, B. S., 131 State St., Boston, Mass.

JOHN E. WOLFF, Ph. D., Cambridge, Mass.; Professor of Petrography and Mineralogy in Harvard University and Curator of the Mineralogical Museum. December, 1889.

JOSEPH E. WOODMAN, S. D., Halifax, N. S.; Assistant Professor of Geology and Mineralogy, Dalhousie University. December, 1905.

ROBERT S. WOODWARD, C. E., Washington, D. C.; President of the Carnegie Institution of Washington. May, 1889.

JAY B. WOODWORTH, B. S., 24 Langdon St., Cambridge, Mass.; Assistant Professor of Geology, Harvard University. December, 1895.

FREDERIC E. WRIGHT, Ph. D., Washington, D. C.; Geo-physical Laboratory, Carnegie Institution. December, 1903.

*G. FREDERICK WRIGHT, D. D., Oberlin, Ohio; Professor in Oberlin Theological Seminary.

GEORGE A. YOUNG, Ph. D., Ottawa, Canada; Geologist, Geological Survey of Canada. December, 1905.

FELLOWS DECEASED

*Indicates Original Fellow (see article III of Constitution)

*CHARLES A. ASHBURNER, M. S., C. E. Died December 24, 1889.

CHARLES E. BEECHER, Ph. D. Died February 14, 1904.

AMOS BOWMAN. Died June 18, 1894.

*J. H. CHAPIN, Ph. D. Died March 14, 1892.

*EDWARD W. CLAYPOLE, D. Sc. Died August 17, 1901.

GEORGE H. COOK, Ph. D., LL. D. Died September 22, 1889.

*EDWARD D. COPE, Ph. D. Died April 12, 1897.

ANTONIO DEL CASTILLO. Died October 28, 1895.

*JAMES D. DANA, LL. D. Died April 14, 1895.

GEORGE M. DAWSON, D. Sc. Died March 2, 1901.
Sir J. WILLIAM DAWSON, LL. D. Died November 19, 1899.
*WILLIAM B. DWIGHT, Ph. B. Died August 29, 1906.
*GEORGE H. ELDRIDGE, A. B. Died June 29, 1905.
*ALBERT E. FOOTE. Died October 10, 1895.
*HOMER T. FULLER. Died August 14, 1908.
N. J. GIROUX, C. E. Died November 30, 1890.
*JAMES HALL, LL. D. Died August 7, 1898.
JOHN B. HATCHER, Ph. B. Died July 3, 1904.
*ROBERT HAY. Died December 14, 1895.
*ANGELO HEILPRIN. Died July 17, 1907.
DAVID HONEYMAN, D. C. L. Died October 17, 1889.
THOMAS STERRY HUNT, D. Sc., LL. D. Died February 12, 1892.
*ALPHEUS HYATT, B. S. Died January 15, 1902.
*JOSEPH F. JAMES, M. S. Died March 29, 1897.
WILBUR C. KNIGHT, B. S., A. M. Died July 28, 1903.
RALPH D. LACOE. Died February 5, 1901.
*JOSEPH LE CONTE, M. D., LL. D. Died July 6, 1901.
*J. PETER LESLEY, LL. D. Died June 2, 1903.
HENRY MCCALLEY, A. M., C. E. Died November 20, 1904.
OLIVER MARCY, LL. D. Died March 19, 1899.
OTHNIEL C. MARSH, Ph. D., LL. D. Died March 18, 1899.
JAMES E. MILLS, B. S. Died July 25, 1901.
*HENRY B. NASON, M. D., Ph. D., LL. D. Died January 17, 1895.
*PETER NEFF, M. A. Died May 11, 1903.
*JOHN S. NEWBERRY, M. D., LL. D. Died December 7, 1892.
*EDWARD ORTON, Ph. D., LL. D. Died October 16, 1899.
*RICHARD OWEN, LL. D. Died March 24, 1890.
SAMUEL L. PENFIELD. Died August 14, 1906.
*FRANKLIN PLATT. Died July 24, 1900.
WILLIAM H. PETTEE, A. M. Died May 26, 1904.
*JOHN WESLEY POWELL, LL. D. Died September 23, 1902.
*ISRAEL C. RUSSELL, LL. D. Died May 1, 1906.
*JAMES M. SAFFORD, M. D., LL. D. Died July 3, 1907.
*CHARLES SCHAEFFER, M. D. Died November 23, 1903.
*NATHANIEL S. SHALER, LL. D. Died April 10, 1906.
CHARLES WACHSMUTH. Died February 7, 1896.
THEODORE G. WHITE, Ph. D. Died July 7, 1901.
*GEORGE H. WILLIAMS, Ph. D. Died July 12, 1894.
*J. FRANCIS WILLIAMS, Ph. D. Died November 9, 1891.
*ALEXANDER WINCHELL, LL. D. Died February 19, 1891.
ALBERT A. WRIGHT, Ph. D. Died April 2, 1905.
WILLIAM S. YEATES. Died February 19, 1908.

Summary

Original Fellows	59
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